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An assessment of the 2004 snow crab populations resident on the Scotian Shelf (CFAs 20 to 24)

Évaluation des populations résidentes de crabe des neiges sur la plate-forme néo-écossaise (ZPC 20 à 24) en 2004

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Abstract

Fisheries exploitation has been at all-time highs for the past 4 years, at TACs of approximately 10,000 t/year. Landings (9,629 t) nearly met these TACs (9,657 t) in 2004 with 1,417, 7,914 and 298 t landed in the northern, southern and slope areas, respectively. The catch rates for all of the shelf was 93.1 kg/th derived from approximately 100,200 trap hauls. Catch rates in the northern crab fishing areas (CFAs) were at their lowest levels in the past five years (60.6 kg/th), with the exception of CFA 22 Outer (Glace Bay Hole) which exhibited catch rates of 165.0 kg/th. Catch rates in the southern crab fishing areas (CFAs 23 & 24), increased slightly since the year 2000 (103.0 kg/th). The southern fishing areas continued to expand (spatially) in 2004.

The abundance of snow crab on the Scotian Shelf declined in 2004, continuing the downward trend observed since the peak abundances of the late 1990s and early 2000s. Fishable biomass estimates as of the winter of 2005 stands at approximately 29,000 t, which comprised of 1,600 t in the northern CFAs and 27,700 t in the southern CFAs. Other indicators of the status of the stock were also indicative of a continued decline and disequilibrium: sex ratios were dominated by males with extremely few mature females resident on the system for more than 4 years running, aging of the population with limited signs of rejuvenation, and rapidly increasing exploitation rates (presently, 32 % by biomass). A strong note of caution is advised in the management of the Scotian Shelf snow crab fishery: there are very few signs of recruitment for another 3 to 5 years and therefore greater uncertainty in it's long to mid-term sustainability.

Résumé

L'exploitation du crabe des neiges se maintient à un niveau record depuis quatre ans, le total autorisé des captures (TAC) étant d'environ 10 000 t par année. En 2004, les débarquements ont presque atteint le TAC de 9657 t, les totaux ayant été de 1 417, 7 914 et 298 t dans les zones du Nord, du Sud et de la pente continentale, respectivement. Le taux de capture pour l'ensemble de la plate-forme était de 93,1 kg/casier levé, établi à partir d'un effort d'environ 100 200 casiers levés. Dans les zones de pêche du crabe (ZPC) du Nord, le taux de capture était à son plus bas pour les cinq dernières années (60,6 kg/casier levé), à l'exception de la ZPC 22 extérieure (fosse de Glace Bay) où le taux de capture a été de 165,0 kg/casier levé. Dans les ZPC du Sud (ZPC 23 et 24), le taux de capture a augmenté légèrement depuis 2000 (103,0 kg/casier levé). L'étendue spatiale des zones de pêche du Sud a continué de croître en 2004.

L'abondance du crabe des neiges sur la plate-forme néo-écossaise a continué de diminuer en 2004, suivant la tendance observée depuis les sommets atteints à la fin des années 1990 et au début des années 2000. La biomasse exploitable à l'hiver 2005 est estimée à environ 29 000 t, dont 1 600 t dans les ZPC du Nord et 27 700 t dans les ZPC du Sud). D'autres indices de l'état du stock semblent aussi indiquer une diminution et un déséquilibre continus : le rapport des sexes est dominé par les males et l'on constate très peu de femelles matures résidentes et ce, depuis plus de quatre ans, un vieillissement de la population avec des signes limités de rajeunissement et une accélération rapide du taux d'exploitation (estimé actuellement à 32 % de la biomasse). Une approche très prudente est conseillée pour la gestion de la pêche du crabe des neiges de la plate-forme néo-écossaise, car le recrutement escompté pour les prochaines années est très faible et l'avenir général du stock à moyen et à long termes paraît donc encore plus incertain.

1 Introduction

The mandate to provide scientific advice as it pertains to the Scotian Shelf snow crab population was transferred in 2004 from the Gulf Fisheries Centre (GFC; Moncton, New Brunswick) to the Bedford Institute of Oceanography (BIO; Dartmouth, Nova Scotia).

This report documents the currently understood (1) **status** of the snow crab resident on the Scotian Shelf (Figure 1) from fisheries data and a dedicated trawl survey; and (2) the **regulating factors** (anthropogenic and environmental processes) that potentially control their abundance.

2 Ecology and life history

The snow crab (*Chionoecetes opilio*, Brachyura, Majidae, O. Fabricius) is a subarctic species resident along the east coast of North America from northern Labrador to the Gulf of Maine. On the Scotian Shelf, commercially fished snow crab are observed between depths of 50 to 300 m and between temperatures of -1 to 6 °C (Figure 2). Near 7 °C, metabolic costs are thought match metabolic gains (Foyle et al. 1989). Snow crab are generally observed on soft mud bottoms although small-bodied and moulting crabs are also found on more complex (boulder, cobble) substrates.

Diet studies and field observations (Hooper 1986; Bundy 2004) indicate that the primary food items of larger (mature) crab are, in order of importance: echinoderms, polychaete worms (*Maldane* sp., *Nereis* sp.) and other worm-like invertebrates, small benthic invertebrates, detritus, large zooplankton, shrimps, smaller crabs (Rock crab, *Cancer irroratus*; Toad and Lesser toad crabs, *Hyas coarctatus*, *Hyas araneus*), ocean quahog (*Artica islandica*), bivalve molluscs (e.g., *Mytilus edulis*, *Modiolus modiolus*, brittle stars (*Ophiura sarsi*, *Ophiopholis aculeata*) and sea anemones (*Edwardsia* sp., *Metridium senile*). Smaller crabs primarily feed upon, in order of importance: echinoderms, polychaete worms, large zooplankton, detritus and bivalves (e.g., *Mytilus edulis*, *Modiolus modiolus*, *Hiatella arctica*). More recent studies have also demonstrated that cannibalism is highly prevalent in intermediately sized (morphometrically) mature crabs, especially mature females (Sainte-Marie and Lafrance 2002; Squires and Dawe 2003).

The known predators of snow crab are, in order of importance: Atlantic halibut (*Hippoglossus hippoglossus*); skates (especially thorny skate, *Raja radiata*), Atlantic cod (*Gadus morhua*), seals, American plaice (*Hippoglossoides platessoides*), squids, and other crabs (Bundy 2004). Studies of the diet of Atlantic cod and thorny skate have suggested their capacity to control the recruitment of snow crabs; they have been implicated in causing weak age-classes (missing instars) and eventually declines in commercial catch rates (Bailey 1982; Lilly 1984; Robichaud et al. 1989, 1991). Robichaud et al. (1991) have shown that snow crab in the size range of 5 to 30 mm CW (7 mm CW mode; that is instars 2 to 7, with instar 7 being strongly selected) were targeted by thorny skate and cod and that during the spring season, soft-shelled male snow crab in the size range of 77 to 110 mm CW were also preferentially targeted.

Snow crab eggs are brooded by their mothers for 2 years or more, depending upon ambient temperatures, food sources and the maturity status of the mother (27 months in primiparous females - first breeding event, and 24 months in multiparous females - second or possibly third breeding events; Sainte-Marie 1993). In some systems, more rapid development of eggs has been suggested, from 12 to 18 months (Elner and Beninger 1995). A primiparous female of approximately 57 mm carapace

width (CW) would produce between 35,000 to 46,000 eggs which are extruded between February and April (in the Baie Sainte-Marguerite; Sainte-Marie 1993). The actual range of fecundity is however quite large, especially as multiparous females are thought to be more fecund with more than 100,000 eggs being produced by each female. Eggs are hatched from April to June when they become pelagic (zoea stages 1 and 2 and then the megalopea stage) feeding upon the plankton for 3 to 5 months, after which time they settle to the bottom (September to October in the Gulf area; on the Scotian Shelf pelagic stages seem highest in October (Figure 3) and so presumably they settle to the bottom some time near January). Very little is known of survival rates at these early life stages.

In the early bottom dwelling stages (benthic postlarval stages or "instars" 1 to 5; where instar 1 is approximately 3 mm CW and instar 5 is approximately 15 mm CW), crabs moult approximately twice a year (Sainte-Marie et al. 1995; Comeau et al. 1998). Crabs after the 5th instar generally moult once a year and reach a terminal size between the 9th to the 14th instar in males (9th to 10th instar in females). Males become sexually mature by the 11th instar (10th instar in females). Just prior to the terminal moult, male crab may skip a moult in one year to moult in the next (Conan et al. 1992). Snow crab generally reach legal size by the 12th instar, representing an age of approximately 9 years since settlement to the bottom and 11 years since egg extrusion. Thereafter, the life expectancy of a male is approximately 5 to 6 years. Up to 10 months are required for the shell to harden (Carapace conditions 1 and early 2) and up to 1 year for meat yields to be commercially viable as the body content is primarily water during the soft-shell phase. After hardening of the carapace (Carapace conditions late 2 to 4), the male is able to mate. Near the end of the lifespan of a snow crab (Carapace condition 5), the shell decalcifies and softens, often with heavy epibiont growth (see Table 1).

Females reproducing for the first time (primiparous females) generally reach a final size of approximately 55 mm CW (Comeau et al. 1998) in their terminal moult and mate while their carapace is still soft (between December to April). A second mating period later in the year (May to June) has also been observed for multiparous females (Hooper 1986). Complex behavioural patterns have also been observed: the male helps the primiparous female moult, protects her from other males and predators and even feeds her (indirectly; Hooper 1986). Pair formation (a mating embrace where the male holds the female) may occur up to 3 weeks prior to the mating event (Hooper 1986). Upon larval release, males have been seen to wave the females about to help disperse the larvae. Females are selective in their mate choice (as is often the case in sexually dimorphic species) and have been seen to die in the process of resisting mating attempts from unsolicited males (Watson 1972; Hooper 1986). Males compete heavily for females and often injure themselves (losing appendages) while contesting over a female.

3 The fishery

The snow crab fishery in eastern Canada began in 1960 with incidental by-catches by groundfish draggers near Gaspé, Quebec (Elner and Bailey 1986). Its development was slow until the 1980s when it began expanding rapidly to become one of the largest fisheries in Canada (93000 t in 2001; Dufour and Dallaire 2003). In Nova Scotia, the fishery has been in existence since the late 1970's (Figure 4). The earliest records of landings were at levels of < 1000 t. By 1979, this rose to 1500 t subsequent to which the fishery declined substantially in the mid-1980s. Strong recruitment to the fishery occurred in 1986 and since that time, landings have increased considerably. Presently, landings have stabilised at > 10000 t each year.

The Scotian Shelf has been subdivided into numerous management areas (crab fishing areas or CFAs;

Figure 5). The management of these fisheries was based on effort controls (season, license, trap limits) from 1982 to 1993. Additional management measures were introduced from 1994 to 1999: individual boat quotas (IBQs), total allowable catches (TACs), 100% dockside monitoring, mandatory logbooks, at-sea monitoring by certified observers and the introduction of sub-areas to ensure distribution of fishing effort. Voluntary management measures requested by fishermen were also introduced in some areas (e.g. CFA 21), such as a shortened fishing season and reduced numbers of traps.

Landings doubled from 1997 to 1999 with new temporary allocations being granted in CFAs 20, 23 and 24 to fishing grounds outside of the traditional fishing grounds. In 1999, a trawl survey was used for the assessment of the snow crab stock on the Scotian Shelf. The survey demonstrated the presence of unexploited stocks to the south-east areas of the shelf. As a consequence, TACs and IBQs increased from 900 t to 1015 t in the north and from 2700 t to 8800 t in the south between 1999 and 2000. Following voluntary trap surveys in 2000, additional allocations (200 t) were made in 2001 and 2002 with further additions in 2003 of 300 t. Thus the *post-1998 period was one of rapid expansion* of both the economic importance of the crab fishery and also the spatial range of exploitation.

Decreases in the abundance of immature males were detected from 1997 to 2002 while the abundance of legal size males remained stable. Trends in catch rates continued to increase during this period (Figure 6) as did fishing effort (Figure 7). Annual TACs remained at 8,800 t in the south but increased to 1,500 t in the north. In 2004, due to signs of poor recruitment and consistently lower catch rates in most areas, a 10% reduction in TACs was implemented. CFA 22 Outer (Glace Bay Hole) was an exception to this rule, with an increase of 15% in TAC due to locally very high catch rates. The CFAs 24A and 24B were combined in 2004 for management purposes but remain as distinct units in this document for comparative purposes. The division of CFA 20 into inside and outside areas was removed in 2004 by agreement of the fishers operating in these areas. Minor changes to some of the sub-area fishing seasons also occurred in 2004. The management measures for 2004 are summarised in Table 2.

4 Methods

4.1 Analytical tools

Visualisations of maps were constructed with GMT (Wessel and Smith 1998, version 4) with the *splines-in-tension* data smoothing and interpolation technique (tension parameter T set at 0.4 and a spatial extent of interpolation of 20 km radius from every datum, a range comparable with that observed in the empirical variograms; see below). Conversions between cartographic and cartesian co-ordinate systems for analytical purposes were computed with PROJ (Evenden 1995, version 4.4.9), using a Lambert conformal conic projection and the WGS84 spheroid with the central meridian at 63°W and standard parallels at 43°N and 47°N. All other data analyses were implemented in the statistical computing language and environment R (Team 2004, version 2.0.1) to allow migration and documentation of methods into the future. Kriging was conducted with the R package, GSTAT (Pebesma 2004, version 0.9-18). All analytical tools were open-sourced software.

4.2 Fisheries data

Catch rates are biased indicators of abundance as (1) both the spatial and temporal distribution of crabs and the fishing effort (Figure 5) are not uniform; and (2) the spatial range of crab distribution varies strongly with time (associated with temperature constraints, food availability, reproductive behaviour, substrate/shelter). Nonetheless, to maintain continuity with historical records, they are here presented. Mandatory logbooks provide information on location, effort (number of trap hauls) and landings (verified by dockside monitoring). The data are stored in the Maritime Fisheries Information System (MARFIS) of the Maritimes Branch Statistics Division of DFO. Exhaustive data quality checks were completed. Catch rates (kg th^{-1}, where "th" is trap haul) were computed as the ratio of total landings to total trap hauls, using data from properly completed logbook records. Catch rates are reported without standardisation. Logbook records with properly completed effort data comprised 91.9% of total ENS (Eastern Nova Scotia) landings in 2004. Catch rate data is not presented from the ENS slope trap survey due to the limited comparability between years and with other areas as trap hauls were made at predetermined survey locations and depths. Total trap hauls for a given group is computed by dividing the total landings by their respective catch rate.

At-sea-observer data provided information about the size structure and the carapace condition of the commercially exploited stock. The data are stored in a centrally organised relational database (Observer Database System). At-sea-observers are deployed randomly (Figure 8) with the coverage being as evenly distributed between CFAs as possible. The target coverage (by quota) was 5% and 10% for the northern and southern areas, respectively. Two types of samples are collected during commercial fishing trips, sea samples and process samples. Sea samples randomly sample 40 snow crabs from a randomly chosen trap, *before* being sorted by the fisher; whereas process samples randomly sample 20 snow crabs *after* selection by the fisher for retention. Catch rates (from the at-sea-observer data stream) are estimated from counts of the traps hauled and an estimated weight of kept and discarded snow crab recorded for each set.

4.3 Research survey data

4.3.1 Dedicated snow crab trawl surveys

Dedicated trawl surveys are the primary data source used for assessment of snow crab on the Scotian Shelf. First introduced by the GFC in 1996 (Biron et al. 1997), it is funded by the fisheries through a Joint Project Agreement. Spatial coverage in the survey is (1) **extensive**, going well beyond all known commercial fishing grounds and (2) **intensive**, with a minimum of one survey station located pseudo-randomly in every 10 x 10 minute area to facilitate geostatistical estimation techniques (i.e., *kriging*; Legendre and Legendre 1998; Kern and Coyle 2000; Venebles and Ripley 2002).

Unfortunately there has been an evolution in survey extent, intensity and timing rendering direct inter-annual comparisons of the data difficult. The survey is conducted in the autumn (September to November; i.e. post-fishing season in CFAs 20 to 24 and just prior to the fishing season in CFA 4X). The timing of the surveys have stabilised to this period only since 2002, prior to which sampling was conducted during the spring (April to July; i.e., pre-fishing season in CFAs 20 to 24). Thus time trends are most reliable for the period since 2002. Further, the trawl survey coverage of CFA 4X has been sporadic and a renewed effort has been made to stabilise the spatial coverage in this area.

With respects to the sampling design (especially point 1 above), questions have been repeatedly raised

as to the need of sampling areas where crabs are unlikely to occur in commerically viable concentrations – the concern being that these additional stations will bias the biomass estimates towards smaller values. The reality is that:

1. Geostatistical techniques such as *Kriging* do not necessarily bias estimates of biomass to lower values. Their application limits the spatial range of influence of sampled biomasses (the spatial scales were found to range from 10 to 50 km radius which also corresponds to the average movement distances of 58 km based upon tagging studies). That is, having many zero catches of crab in a given area only make more certain that they do not exist in high numbers in that area and that area only. Global biomass estimates are not necessarily biased downwards and may in fact be biased upwards as the spatial extent of the influence of a zero value catch may be less than that based upon a simple assumption that a large area contains no crab.

2. The spatial bounds of the snow crab population must be known if reliable estimates of biomass and population structure (e.g., size, sex, maturity) are to be made. The errors associated with extrapolation are generally much higher than those of interpolation as the latter are bounded by measured values while the former are not.

3. As observed by many fishermen in the year 2003, the distributional extremes of crab seem quite dynamic (most likely due to temperature variations) and so can shift to areas where they are not "traditionally" found. For the purposes of monitoring such changes in distribution, sampling is required even in areas where crab have not been previously observed.

4. The distributional patterns of immature, soft-shelled, very old and female crabs do not correspond directly to that of legal size males. These individuals are considered to be less competitive and more susceptible to predation (Hooper 1986) and observed in more marginal environments or substrates with greater cover (gravel, rocks; Comeau et al. 1998). Focusing upon only those areas where large hard-shelled males occur in high frequency would preclude the reliable estimation of the relative abundance of these other important segments of the crab population.

A *Bigouden Nephrops* trawl, a net originally designed to dig into soft sediments for the capture of lobsters in Europe was used to sample the substrate (headline of 20 m, 27.3 m foot rope mounted with a 3.2 m long 8 mm chain, with a mesh size of 80 mm in the wings and 60 mm in the belly and 40 mm in the cod-end). Tows were conducted for $\sim$ 5 minutes in duration with actual duration of bottom contact being monitored using Netmind sensors. The width of the mouth of the net was also monitored with Netmind sensors. The ship speed was maintained at $\sim$ 2 knots. The warp length was $\sim$ 3 times the depth (as from a bottom sounder). Positional information as well as water temperature measurements were collected using geographic positioning systems and Minilog data recorders, respectively. The surface area swept by the net was calculated from swept distance and net width information.

All crabs were enumerated, measured with calipers, shell condition described, claw hardness determined with a durometer and weighed with motion-compensated scales. The latter allowed direct biomass measurement rather than estimates relying upon allometric relationships between body parts. Other species caught were also identified, enumerated and weighed. Data entry and quality control was provided by JaviTech and migrated onto the Observer Database System, held at DFO (BIO).

Pre-2004 snow crab biomass estimates were approximated from carapace width measurements by applying the allometric relationships developed for the Scotian Shelf adult hard shelled snow crab (Biron et al. 1999; $R^2 = 0.98$, $n = 750$):

$$mass[g] = 1.543 \times 10^{-4} \times (carapace\ width[mm])^{3.206} \quad (1)$$

The maturity status of males was determined from morphometric maturity. While physiological maturity is not directly co-incident with the onset of morphometric maturity (morphometrically immature male crabs are more than capable of mating in the absence of competition from terminally moulted males Sainte-Marie 1993), the latter is more readily quantified. In the terminal molt of male snow crabs, a disproportionate growth increment in chela height (CH) relative to carapace width (CW) is generally observed (which may be associated with increased mating and/or reproductive success). Such morphometrically mature males can be discriminated from those that have not undergone the rapid chela growth via the following equation (E. Wade, personal communication, GFC):

$$M_{male} = -25.324 * ln(CW[mm]) + 19.776 * ln(CH[mm]) + 56.650 \quad (2)$$

where the individual is considered mature if $M_{male} > 0$.

The maturity status of females is assessed from direct visual inspection of eggs or gonad development. Where maturity status was ambiguous, maturity was determined morphometrically, as the width of abdomen (measured by the width of the fifth abdominal segment, AW) increases rapidly relative to carapace width (CW) at the onset of morphometric maturity, facilitating the brooding of eggs. This onset of morphometric maturity can be delineated via the following equation (E. Wade, personal communication, GFC):

$$M_{female} = -16.423 * ln(CW[mm]) + 14.756 * ln(AW[mm]) + 14.900 \quad (3)$$

where the individual is considered mature if $M_{female} > 0$.

Sex ratios (proportions) were calculated as:

$$Sex\ ratio_{(immature)} = \frac{N_{(female,\ immature)}}{N_{(female,\ immature)} + N_{(male,\ immature)}} \quad (4)$$

$$Sex\ ratio_{(mature)} = \frac{N_{(female,\ mature)}}{N_{(female,\ mature)} + N_{(male,\ mature)}} \quad (5)$$

where N are the numbers of crab of each category.

Recruitment categories are as those defined in Hébert et al. (2004) where R1 is the segment of the population expected to enter the commerical fishery in the next year, R2 in two years, R3 in three years, etc (see Recruitment in the Glossary). Size-frequency histograms were constructed (expressed as number per unit area swept by the trawl (km^{-2}); i.e., the arithmetic mean numerical density per unit area in each size interval).

The locations of "most likely snow crab habitats" were determined on high resolution depth maps (15 arc-second resolution) obtained from the Canadian Hydrographic Service. The range of observed depths of Scotian Shelf snow crab (between 50 m to 300 m; Figure 2, left panel) were used to delineate

these potential snow crab grounds. For each year, maps of preferred snow crab temperature locations were made using Optimally Estimated bottom temperature maps (obtained from the Ocean Science Division of BIO, DFO). Preferred snow crab temperatures on the Scotian Shelf ranged between $-1°C$ to $+6°C$ (Figure 2, right panel). These two sources of information were combined to delineate the most probable locations of snow crab habitat (Figure 20). This dynamically changing habitat range was used to predict the biomass and numerical densities of crab.

The estimation of biomass and numerical densities involved the use of geostatistical methods: modelling of variograms (the behaviour of variance as a function of distance) for each of the individual variables in each year. Variograms were constructed to a spatial extent of 50 km radius, which was sufficient for the expression of the asymptotic increase of variance (sill). An automated process was developed to choose a functional form (Bessel, spherical, exponential, circular, gaussian or generalised-Matern) that best described the spatial variance using a nonlinear least-squares criterion. Spatially explicit means and variances were then obtained from Point Kriging and used for mapping and modification of sampling designs. Ordinary Block Kriging, using blocks of $1km^2$ resolution was subsequently used to estimate the biomass and numerical densities and the associated standard deviations for the areas of most probable snow crab habitats.

Ordinary Block Kriging standard deviations were used for the estimation of the 95% confidence intervals in the predicted intensive variables (biomass and numerical densities). Problems of convergence of solutions were observed for the majority of intensive variables due to sparse spatial coverage (immature, female, CC1 and CC5 crabs; where CC indicates carapace condition; see Table 1). Thus, kriged abundances were only found to give reliable solutions for legal size crabs as they were the most abundant in number and biomass. For those variables where a reliable or realistic solution was not observed, simple means and standard deviations (arithmetic and geometric, where appropriate) were presented.

Relative exploitation rates (ER) were calculated as:

$$ER_{(t)} = Landings_{(t)}/Fishable\,biomass_{(t-1)} \tag{6}$$

where t is time; Landings are the total landed snow crab in year t; and Fishable biomass is the total biomass of the legal sized segment of the male population $\geq$ 95 mm CW, estimated from kriging for year t.

4.3.2 Supplementary data sources

Randomised depth-stratified research surveys of commercial and non-commercial fish species resident on the Scotian Shelf have been conducted in the summer season by DFO from 1970 to the present. This data is the primary source of information for stock assessments of many demersal (bottom-dwelling) fish species and was used to corroborate the historical snow crab biomass trends observed by the dedicated snow crab surveys. This data is maintained by the Marine Fish Division (BIO Science, DFO).

Plankton on the Scotian Shelf has been monitored sporadically in time and space. This information is resident on the BIOCHEM databases and is maintained by the Atlantic Zonal Monitoring Program and BIO. The taxonomic resolution of these samples were poor. As a consequence, we use the relative

abundance of Brachyura larvae as a proxy for the relative abundance of snow crab larvae. This data is courtesy of B. Petrie (Ocean Sciences Division, BIO Science, DFO).

5 Resource Status

5.1 Fisheries data

5.1.1 Spatial distribution of fishing effort

The spatial distribution of fishing effort was comparable between the years 2003 and 2004. Some greater dispersion of the locations were evident in 2004, especially in CFAs 22 Outer, 23A, 24A and 24E (Figure 5). Relative to 2003, a distinct lack of fishing activity was evident in CFA 20 Outside and increased activity seen in CFAs 20 Inside, 21 and 22 Inner. Overall, an expansion of the area exploited occurred, co-incident with new management measures in 1998 onwards (see Introduction and Figures 10, 11 and 12).

5.1.2 Landings

The total landings for CFAs 20 to 24 were 9331 t (relative to 10318 t in 2003; Figure 4) and each CFA has continued to reach their respective TACs (Tables 3 and 4). Landings for CFAs 20 to 22 were 1417 t, down 6% from 2003 (reflective of the reduced TAC). Landings for CFAs 23 and 24 were 7914 t and total calculated effort was 76300 trap hauls. The landings from the allocations associated with the ENS slope trap survey were 179.2 t for CFA 24 (3 participants) and 118.3 t CFA 23 (2 participants).

5.1.3 Catch rates

The catch rate for all of ENS (CFAs 20 to 24) was 93.1 kg/th derived from approximately 100200 trap hauls (Figures 6, 7). In the northern CFAs (20 to 22), catch rates were at the lowest level in the past five years (60.6 kg/th). Calculated fishing effort was at its highest level (approximately 23400 trap hauls) in 2004 (Table 3). The total catch rates by sub-area for ENS are given in Table 5. The catch rate for sub-area 22 Outer (Glace Bay Hole) in 2004 was the highest in N-ENS and in the five year historical record, at 165.0 kg/th. Conversely, 2004 catch rates for CFAs 20, 21 and CFA 22 Inner were at the lowest levels in the five year historical record.

In the southern CFAs (23 & 24), catch rates have generally increased since 2000. The catch rate for 2004 (103.0 kg/th) was above the five year mean and represented a 7% increase over 2003 levels (Table 4). The highest catch rates were observed in CFAs 23B, 23C, 24B and 24D. The total catch rate for all of CFA 23 increased from 2003 to 2004 (98.7 to 114.1 kg/th), while the total catch rate for CFA 24 showed little change between 2003 and 2004, at approximately 92 kg/th (Table 5). The trends in catch rates by sub-area in S-ENS since 2000 were variable. Stable or increasing catch rates were generally observed in core areas and decreasing catch rates on the margins of the spatial distributions, with the exception of slope edge areas (Figure 10, 11 and 12).

5.1.4 Size structure

In N-ENS, 5.9% of the quota was observed (Table 6). A total of 95 traps were sampled (0.41% of commercial trap hauls) and 3750 male snow crabs were sampled. Of the sampled crab, 89.5% were

of legal commercial size. The mean CW of these legal size crab increased in all CFAs relative to 2003 (Figure 13).

In S-ENS, 10.2% of the quota was observed (Table 6). A total of 711 traps were sampled (0.92% of commercial trap hauls). Of a total of 27535 male snow crabs sampled, 92.4% were of legal size. The mean CW of these legal size crab increased slightly in both CFAs 23 and 24 relative to 2003 (Figure 13).

5.1.5 Carapace condition

In N-ENS, the relative number of CC3 crabs dropped from 79.5% in 2003 to 70.0% in 2004, whereas CC4 increased from 15.7% to 23.4% (Figure 14). In S-ENS, the relative number of CC3 crabs dropped slightly from 78.9% in 2003 to 74.9% in 2004 whereas CC4 increased slightly from 14.3% to 17.8% (Figure 15).

5.1.6 Logbook-derived catch rates vs. observer-derived catch rates

The sampling of the total number of commercial trap hauls was low (0.42% and 0.92% in the north and the south, respectively). Target observer coverage was met. However, due to the logistics of observer deployments, observer coverage was more intensive in the beginning of the fishery in the northern CFAs. This was due to the relatively low number of fishing days required to catch the TACs. As catch rates generally decline over the season in the northern CFAs, the observer-based catch rate estimates were generally higher than those calculated from logbooks.

In the southern CFAs, observer coverage was more uniformly distributed over the course of the fishing season as were the catch rates over the fishing season. A comparison of observer-derived catch rates with logbook-derived catch rates indicated deviations of 1.6% and by 9.7% in CFAs 23 and 24, respectively (Table 7). Further, the proportion of a catch that should be retained based upon commercial viability (durometer reading > 68 and CW ≥ 95 mm) from sea samples were comparable in magnitude with what was actually retained by the fishers for both the northern CFAs (90.6% and 88.0%, respectively) and the southern CFAs (92.6% and 89.1%, respectively).

5.1.7 Summary of fisheries data

Overall, catch rates demonstrated a downward trend in the northern CFAs since 2002 (with the exception of CFA 22 Outside) while the fishing grounds have remained stable over time. In contrast, an increasing trend in catch rates was evident in the southern CFAs (with the exception of CFAs 24C and 24E). This however is strongly associated with a spatial expansion of the fishery (offshore areas of the southern CFAs) exploiting previously exploited areas.

The increase in mean carapace width of legal-size snow crab as well as the increased proportion of CC4 crab relative to 2003 is suggestive of a population with little recruitment. While this may be the case in the northern CFAs, the spatial expansion of the fisheries, in the southern CFAs confounds this observation as the exploitation of previously unexploited populations can bias mean size and carapace conditions towards larger older/dirtier individuals (e.g., on the slope edge, the tendency for very rapid fouling of carapaces has been noted). Further, as sea samples come from commercial snow crab traps,

it represents only the portion of the snow crab population which is readily caught in such traps and therefore is inherently biased and not representative of the entire snow crab population.

5.2 Research survey data

5.2.1 Size structure

The average size (CW[mm]) of morphometrically mature male and female snow crabs on the Scotian Shelf has been increasing steadily since 1997 (males) and 1996 (females), when the main wave of recruitment into the mature population began (see below; Figure 16). Crabs have since been maturing with little recruitment into the morphometrically mature population. However, in 2004, the first signs of a rejuvenation of morphometrically mature female of the population was evident with the strong decline in average size to about 55 mm CW. This return of new and very small mature females, was centered upon the near-shore areas of CFAs 23A and 24A, near Chedabucto and Gabarus Bays (Figure 17).

For the northern CFAs, temporal variations in size frequency distributions of males (Figure 18) indicated that the males centered over 20 and 30 mm CW (instars 6 and 7, respectively) in 2003 successfully moulted and carried over into 2004 into the 30 and 38 mm CW modal groups. Based upon established growth patterns, these two modes should reach legal size in five and four years, respectively. However, another weaker mode near 50 mm CW was evident (instar 9), a group that should reach legal size in three years time. Very little recruitment in the intervening years is expected. A very similar pattern was evident for the southern CFAs, although proportionately more pre-recruits in the 60 to 80 mm CW range were observed relative to the northern CFAs.

The size frequency distributions of females illustrates the drop in mean CW noted above for mature females (Figure 19). Similar to what was observed for males, in 2003 two modes were evident in the northern CFAs, centered upon 20 and 30 mm CW (instars 6 and 7). The year-classes moulted successfully into the 30 and 40 mm CW size classes in 2004 which should reach terminal moult in 4 and 3 years, respectively (instar 11). A third mode centered over the 50 mm CW size range (instar 9) was also evident in 2004, which should reach terminal moult in one or two years time. A very similar pattern was observed in the southern CFAs, indicative of strong synchrony in the biological cycles of the snow crab throughout the whole of the Scotian Shelf.

5.2.2 Sex ratios

The sex ratio of morphometrically mature snow crabs (no. mature females / (no. mature males + no. mature females)) has decreased rapidly on the Scotian Shelf (Figure 21) after an initially balanced ratio in the late 1990s. This downward trend was observed uniformly, throughout the Scotian Shelf for the past four years. What is currently worrisome is that encounter rates between mature snow crab will be very low. In the late 1990s and early 2000s, a very heterogeneous distribution of sexes were observed: pockets of male dominated areas mixed with pockets females dominated areas. During mating periods, mature crab would therefore be able to find the other sex with minimal movement. Currently, a crab would have to move much greater distances to find a mate. This may in part be associated with some of the very large movements of snow crab found on the Scotian Shelf (relative to the Gulf of St. Lawrence).

This decline in sex ratios is concordant with a cyclic population dynamics where females mature more rapidly than males. Thus, the (weak) trend towards a more balanced sex ratios evident in a few locales in 2004 is potentially indicative of return to an increasing phase in the population dynamics (Figure 22). The key conservation related issue being: whether there will be enough large mature males to reproduce with and protect the more rapidly maturing females (primiparous females mate during their moulting stage when they are vulnerable without protection from a large male).

It is surprising that such a strong bias in the sex ratio was also present amongst immature crabs (Figures 21 and 22). As their ecology and growth patterns are quite similar at the early immature stages, there should not be sex-biased differential mortality. However, the sizes that the trawl can capture are in the range of 30 mm CW or more, a size range where differential growth rates begin (8th instar; Sainte-Marie et al. 1995; Comeau et al. 1998). Thus immature females may be more susceptible to predation than males of the same year-class as they stay at smaller sizes for longer periods. This suggests that heavy predation may have been a cause of this decline, a decline which has since re-stabilised (e.g., potentially via cannibalism as snow crabs were at record abundances in the time frame of 1997 to 1999, but not likely groundfish due to their low numbers).

An important consequence of the extended period of very low sex ratios observed throughout the Scotian Shelf is that very poor larval production in the system likely occurred for at least a four year period. If indeed, the shelf represents an internally regenerating system (as one must assume until proven otherwise), this may likely entail very poor recruitment into the fishable biomass in the early 2010s. This would represent a good empirical test of the relative importance of internally generated larval production vs. flow from the upstream Gulf of St. Lawrence region.

5.2.3 Fishable biomass

Biomass estimates from DFO's summer groundfish research surveys were used to construct temporal trends of snow crab abundance (Figure 9). Tremblay (1997) examined the spatio-temporal patterns of snow-crab abundance prior to the commencement of the dedicated snow crab surveys and demonstrated the temporal and spatial expansion of the snow crab since the early 1980s. He attributed the expansion to a combination of ameliorating temperature environments and reduced predation from groundfish. We note the increasing trend that parallels his results, and the catch rates (Figure 6) up to the late 1990s.

This increase in abundance was observed to reach its peak in the late 1990s after which a declining trend in the biomass of legal size and R1 (soft-shelled crab that will enter the fishable biomass in the following year) males were observed (Biron et al. 2004). We have re-scaled this data for the spatial extent of the snow crab habitable area on the shelf in 2004 to obtain the biomass times-series in Figure 23.

The geostatistically estimated biomass of legal size crabs for the year 2004 was 29000 t (with 95% confidence intervals of 25000, 32000 t) for the whole of the Scotian Shelf. By region, the breakdown was: northern CFAs [1600 t (1300, 1900)]; southern CFAs [27700 t (24900, 30900)], which includes the slope biomass estimates of CFA 23 [3100 t (2200, 4500)] and of CFA 24 [2400 t (1500, 3800)]; and CFA 4X [1800 t (1200, 2900)].

The spatial distribution of biomass densities (Figure 24) were quite consistent over time. Greatest variations generally occurred in the inshore areas. Biomass declines were evident in most areas, with the exception of the more recently exploited slope-edge locations.

5.2.4 Numerical abundance

Kriged solutions of numerical abundance were computationally unstable. As such geometric mean trends uncorrected for spatial auto-correlation were examined (Figures 25, 26, 27). All stages from the legal size crabs to R1 recruits, R2 recruits and R3 recruits show a continued decline into 2004 (Figures 28 and 29).

5.2.5 Natural mortality

No data are presently available to describe the natural mortality rates of snow crab on the Scotian Shelf. However, Wade et al. (2003) calculated mean annual natural instantaneous mortality rates to be within the range of 0.26 to 0.48 for legal-sized snow crabs resident in the southern Gulf of St. Lawrence. Based upon diet studies (Bundy 2004), very few natural predators seem to exist for large snow crabs (i.e., legal sized) on the Scotian Shelf. This has been particularly the case since the demise of most large-bodied predatory groundfish from the eastern part of the Scotian Shelf (Choi et al. 2004).

Other potential mortality factors include: seals, overfishing as a consequence of season extensions, unreported landings, by-catch in other fisheries (long-lining, trawling), and exploration and development of oil and gas reserves.

5.2.6 Fishing mortality

Analyses of fishing mortality rates have not been completed. However, a heuristic measure of fishing mortality based upon biomass removal rates (Relative Fishing Mortality) indicates that the Scotian Shelf population has been experiencing rather severely (almost exponentially) increasing mortality rates (Figure 30), even though the population is declining. Current exploitation rates are at 32% (by biomass).

5.3 Summary

5.3.1 Recruitment

The new wave of pre-recruits that may reach the fishable biomass will not enter the fishery for another 3 to 5 years. This pulse is associated with the peak levels of biomass observed in the late 1990s. That is, the recruitment seems to have originated internally from the large numbers of reproductively mature crabs that had existed in the late 1990s. While it is possible that the northern areas may also be influenced by larval drift and benthic migration from the Gulf of St. Lawrence snow crab, this internal synchrony would seem to indicate that the Scotian Shelf is (or at least is capable of acting as) a self-generating system. A sustainable long-term fishery requires a self-sustaining reproductive system; unfortunately, the current state of the snow crab's reproductive system is in poor condition. Very few mature females have been in evidence for four years.

There is a possibility that this lack of reproducing females is due to there having been only one major pulse of crabs in a system that had previously been devoid of snow crabs. This main pulse had their origins in the late 1980s and early 1990s (it takes approximately 9 years or more to reach reproductive size). Unfortunately no other such pulses have been detected between the main pulse and the larval pulse that they generated. This means that the snow crab population is currently quite out-of-balance, in a boom-bust cycle. When a population exhibits such dynamics, they are in an inherently unstable state where their continuity in the system is indeterminate (Choi and Patten 2001). That is, the can be highly susceptible to mortality factors such as environmental variations, predation and fishing resulting in an elevated liklihood of facing local extirpation.

A fisheries dependent only upon recruits makes for a volatile fishery, especially as strong snow crab years classes have so far been separated by 9 to 10 years on the Scotian Shelf. To leave crab on the ground to die is "wasted" crab from an economic point of view. However, their presence can serve to stabilise the population in the long term by maintaining and occupying prime crab habitats, which keep at bay potential competitors in the guise of other crabs or even groundfish and to serve as mates for the more rapidly maturing females.

5.3.2 Sources of snow crab larvae

The potential for hydrodynamic transport of snow crab larvae from the southern Gulf of St. Lawrence to the Scotian Shelf has been studied by J. Chassé (Ocean Sciences Division, BIO, DFO; pers. comm.). By treating larvae as passive particles, he was able to demonstrate that a large number of larvae can be transported onto the Scotian Shelf and deposited in areas of strong eddies (near the Sable Bank area and in the shallow areas further west). While pelagic organisms can maintain their position in a single location in even very strong advective conditions via control of vertical migrations, the possibility of snow crab larvae entering the Scotian Shelf from the Gulf of St. Lawrence region cannot be ignored. However, the biological importance of this upstream flow has yet to be quantified empirically. The possibility of some external sources of larvae does not mean that we can ignore the reproductive potential of the snow crab resident on the Scotian Shelf proper. In fact, the mortality bottleneck seems to be extensive: from eggs up to crabs of the 7th instar (4 years since settling to the bottom; Robichaud et al. 1991) meaning that larval drift would have to be very high if they are to recruit into the fishable biomass.

Planktonic samples from the Scotian Shelf indicate that the number of Brachyuran larvae have been consistently low, even with the assumed constant input from upstream sources, from 1976 to 1996 (with a small pulse being detected in 1980; Figure 31). However, a significant pulse of larval abundance was detected from 1997 to 1999 with peak levels in 1998. This was precisely the same period in which biomass levels of mature males and females on the Scotian Shelf seems to have been at their peak and fishery catch rates began to increase sharply. From this concurrent increase in larval densities and spawning biomass in the system, we surmise that the snow crab resident on the Scotian Shelf is more than capable of being a self-reproducing system, regardless of inputs from other systems. Further the spatial distribution of the larvae are quite pervasive throughout the Scotian Shelf with no declines in abundance with distance form the Gulf of St. Lawrence area (Figure 31).

6 Ecological considerations

6.1 Controlling factors

Anecdotal information from long-standing crab fishers and fishery-based catch rates (Figure 6) suggests that the abundance of snow crab was historically low on the Scotian Shelf (at least in the inshore areas). Increases in catch rates were observed throughout the shelf since the mid-1980s and 1990s in the southern and northern Crab Fishing Areas (CFAs), respectively. As commercially exploitable snow crabs require 9 years or more from the time of settlement to reach the legal size of 95 mm CW (Comeau et al. (1998)), their increasing dominance on the shelf must have had their origins as early as the late-1970s and 1980s (in the southern and northern CFAs, respectively).

These time-lines are perhaps confounded by the expansion of the exploited areas towards increasingly offshore locations with previously unexploited crab populations. However most of this expansion was observed in the post-2000 period when total allowable catches (TACs) and landing increased up to 6 fold relative to the TACs and landings of the 1990s (Figure 4) and a doubling of fishing effort (Figure 7). The catch rate increases observed in the 1980s and 1990s therefore were likely reflecting real increases in their abundance.

The possible causes of this increase in abundance can be broken down into four main categories of influence:

1. **Top-down** influences refer to the role of predators in controlling a population (Paine 1966; Tremblay 1997; Worm and Myers 2003). The capacity of predatory groundfish to opportunistically feed upon snow crab (Robichaud et al. 1991), in combination with their numerical dominance prior to the 1990s (Figure 33), suggests that they indeed could have been an important regulating factor controlling the recruitment of snow crabs. Conversely, the recent demise of the groundfish in the post-1990 period (Figure 33) and the resultant release from predation upon the immature and soft-shelled crabs may have been an important determinant of the current dominance of snow crab on the Scotian Shelf. Certainly, due to the size-selectivity of snow crab predators (Robichaud et al. 1991), crab $>$ 30 mm CW are likely experiencing much less (non-human) predation-related mortality, than in the past. However, the trends of increasing groundfish biomass in the early 2000s (however slight) indicates that predation levels upon small immature crabs are likely to be on the rise (Figure 34).

2. **Bottom-up** influences refer to changes in a population due to resource (food) availability. Large increases in food availability can result in increased crab abundance due to reduced competition for resources. The question is: Have large-scale changes in the productivity of the Scotian Shelf occurred co-incident with the increases in abundance of snow crab? Phytoplankton abundance in the most recent decade (1991- 2001) was considerably higher and more variable than in the 1960s and early 1970s (Figure 35). Very little information has been encountered describing the abundance of potentially important benthic food sources on the Scotian Shelf. However, the recent proliferation of northern shrimp (*Pandalus borealis*), a potential food item of snow crab which has overlapping spatial distributions (Figure 36), co-incident with the rise in abundance of snow crab may be an indication that resource levels for snow crab are high. Certainly their rapid rate of increase would seem to indicate that resource competition may not have been a limiting factor up to the late 1990s. However, the recent declines in their abundance since 2002 may be an indication that some form of a carrying capacity had indeed been reached. This interpretation is of course confounded by the heavy exploitation of crabs at levels of almost the

same order of magnitude as their biomass, a rate that could be driving their rapid decline.

3. **Lateral and internal influences**: the release from competitive interactions with groundfish, other crab species, cannibalism, reproduction-induced mortality (direct and indirect). The diet of snow crab overlap in many ways with that of groundfish, thus the demise of groundfish in the late 1980s and early 1990s would have been doubly beneficial to snow crab: reduction in predation pressure and also resource competition. The spatial distribution of other crabs with overlapping distributions are shown in Figure 37. The centers of high abundance may be areas where interactions may be strong causing resource competition, not only for food but habitat space as well. Of course these interactions are complex in that crabs may also serve as predators upon small snow crab as well as being food items for large snow crab. Nonetheless, where concentrations are elevated, the probability of strong negative (competitive) interactions are greater.

4. **Environmental influences**: altered conditions over extended periods of time have been observed on the Scotian Shelf (Figure 32). Prior to 1986, the shelf was characterised by relatively warm bottom waters, low volume of the cold intermediate layer of water, and a Gulf Stream frontal position close to the shelf. The post-1986 period transitioned to an environment of cold bottom waters, a high volume of cold-intermediate layer waters, and a Gulf Stream frontal position distant from the shelf. The principal cause of the cold conditions is thought to have been along-shelf advection from both the Gulf of St. Lawrence and southern Newfoundland, and local atmospherically-induced cooling. In the southwestern areas (Emerald Basin), the offshore Warm Slope water kept subsurface temperatures relatively warm throughout the 1980s and 1990s, the exception being in 1997-98, when cold Labrador Slope Water moved into the region along the shelf break and flooded the lower layers of the central and south western regions. While this event produced the coldest near-bottom conditions in these Shelf regions since the 1960s, its duration was short, lasting about one year. In addition to these subsurface temperature changes, there have also been important physical changes in the near surface waters. Foremost among these has been the increase in vertical density gradient. For example, the density difference between 0 and 50 m increased to its highest level in the past 50 years during most of the 1990s. This was principally the result of record low salinities in the near-surface waters that were advected onto the Shelf from the Grand Banks. Freshwater discharge into the Gulf of St. Lawrence decreased during the 1990s but its contribution to inter-annual variation in salinities on the Scotian Shelf was likely minimal.

   Juvenile crab (approximately instar 5 or 2 years since settlement) were already there in high numbers in the transitional year of 1986. These crab were therefore the benefactors of environmental amelioration and not caused by environmental change. That is, some other cause had allowed their numbers to build up to very large numbers prior to these environmental changes. What this may be is not yet understood. But certainly, changes in predation pressure seems to be a definite possibility that cannot be excluded.

7 Recommendations

A reduction in exploitation rates would be prudent. Little additional recruitment into the fishable biomass is evident into the foreseeable future. If exploitation rates are reduced, the resultant prolongation of the fisheries would however be counter-balanced by the aging of the snow crabs. However, beyond the simple economic motive, there is (1) the requirement of residency to prevent snow crab habitats from being overtaken by competitors (e.g., other crab species); and (2) the necessity of having

males to mate with the soon to mature females. Thus larval production and recruitment into the fishery a decade into the future may be jeopardized. While thinking ahead a decade in advance may seem to be a bit much to demand, the snow crab fishery has shown itself to be a very proactive and mature industry that now needs to consider its future carefully.

The relative fishing mortality index for the Scotian Shelf snow crab has been increasing rapidly. This has been the case even though the population is in decline into the foreseeable future. While exploitation rates have been quite high on occasion in some areas such as the southern Gulf of St. Lawrence (up to 53% in 2002; Hébert et al. 2004), such high rates occurred during periods of increasing snow crab abundance. Further, the productivity, bottom substrate type, temperature variability and spatial heterogeneity of the Scotian Shelf is quite distinct from the Gulf of St. Lawrence area and therefore should not seen as an equivalent system. This is especially the case as it represents the southern-most limit of the distribution of the species. Caution is advisable if the stabilisation of the snow crab stocks is desired.

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Table 1. Snow crab carapace conditions and their description. Hardness is measured by a durometer.

Carapace condition	Category	Hardness	Description	Age after terminal moult (approx)
1	New soft	< 68	claws easily bent, carapace soft, brightly coloured, iridescent, no epibionts	0 - 5 months
2	Clean	variable	claws easily bent, carapace soft, brightly coloured, iridescent, some epibionts	5 months - 1 year
3	Intermediate	> 68	carapace hard, dull brown dorsally, yellow-brown ventrally, no iridescence, shell abrasion, epibionts	8 months - 3 years
4	Old	> 68	carapace hard, very dirty, some decay at leg joints, some epibionts	2 - 5 years
5	Very old	variable	carapace soft, very dirty, extensive decay, extensive epibionts	4 - 6 years

Table 2. Snow crab management measures on the Scotian Shelf in the year 2004. (P) refers to the permanent fleet and (T) refers to the temporary fleet. Quota are in metric tons. Lic refers to the number of licenses. CFAs 23 and 24 had season extensions in 2004. An additional 300 t was allocated to the offshore slope areas.

Area	Season	Lic(P)	Traps(P)	Quota(P)	Lic(T)	Traps(T)	Quota(T)
20	July 22-Sept 15	5	30	102	5	30	57
21	July 22-Sept 15	32	25	490			
22 Inner	July 22-Sept 15	21	30	429			
22 Outer	July 22-Sept 15	16	30	338			
23	June 1-Oct 18	37	45	2,552	34	45	1,744
24	June 1-Nov 12	34	45	2,342	33	45	1,303

Table 3. Summary of snow crab fisheries activity of the northern CFAs (20 to 22).

Year	Landings (t)	TAC (t)	Licenses	catch rates (kg/th)	Calc. effort (1000 th)
2000	1,017	1,015	79	68.3	14.9
2001	1,066	1,065	80	94.1	11.3
2002	1,492	1,493	80	100.9	14.8
2003	1,501	1,493	80	76.8	19.5
2004	1,417	1,416	79	60.6	23.4
Average	1298.6	1296.4	79.6	80.1	16.8

Table 4. Summary of snow crab fisheries activity of the southern CFAs (23 and 24).

Year	Landings (t)	TAC (t)	Licenses	catch rates (kg/th)	Calc. effort (1000 th)
2000	8,701	8,799	158	85.0	102.4
2001	8,912	8,823	163	88.5	102.9
2002	8,767	8,822	149	110.1	79.6
2003	8,817	8,813	145	95.9	89.6
2004	7,914	7,941	130	103.0	76.8
Average	8622.2	8639.6	149.0	96.5	90.3

Table 5. Detailed summary of snow crab catch rates (kg/th). CFA 23B represent data only from the temporary fleet.

Region	2000	2001	2002	2003	2004
CFA 20	46.9	66.1	67.8	44.0	26.8
CFA 21	65.4	95.0	96.8	77.7	51.0
CFA 22	78.4	106.8	120.0	92.6	99.5
CFA 23	83.4	82.1	117.2	98.7	114.1
CFA 24	86.7	99.3	103.0	92.2	92.3
CFA 20 Inside	56.7	92.1	102.2	48.3	26.8
CFA 20 Outside	36.3	46.3	38.9	12.9	No fishing
CFA 22 Inner	68.4	89.9	116.4	81.0	76.8
CFA 22 Outer	104.0	137.0	127.1	120.6	165.0
CFA 23A	102.6	113.1	141.9	94.5	111.6
CFA 23B	99.9	97.8	134.0	120.1	126.1
CFA 23C	65.6	136.3	108.2	134.8	122.7
CFA 23D	62.4	47.3	76.6	71.8	93.1
CFA 24A	81.8	108.8	132.1	78.9	81.5
CFA 24B	99.6	126.1	138.1	133.7	129.0
CFA 24C	90.3	97.5	92.9	85.5	69.2
CFA 24D	83.3	88.6	89.4	126.1	130.7
CFA 24E	50.8	65.6	55.1	46.0	37.9

Table 6. Summary of at-sea-observer coverage in 2004.

CFA	Quota (t)	Landings obs. (t)	% Quota obs.	Trap hauls	Trap hauls obs.
20	159	11.28	7.1%	5900	18
21	491	19.56	4.0%	9600	45
22 Inner	429	20.71	4.8%	5600	22
22 Outer	338	32.53	9.6%	2000	10
23	4273	438.89	10.3%	37600	295
24	3646	365.04	10.0%	39300	416

Table 7. Comparison of catch rate estimates derived from logbook data and at-sea-observer sea samples for in 2004.

CFA	Logbook catch rates (kg/th)	Observer catch rates (kg/th)
20	26.8	43.0
21	51.0	59.0
22 Inner	76.8	111.3
22 Outer	165.1	248.7
23	114.1	112.2
24	92.3	101.8

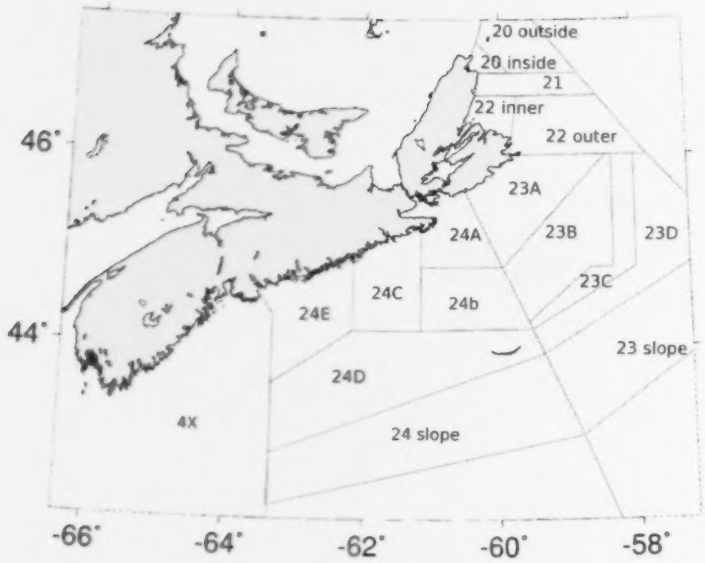


Figure 1. Location of management crab fishing areas (CFAs) on the Scotian Shelf.

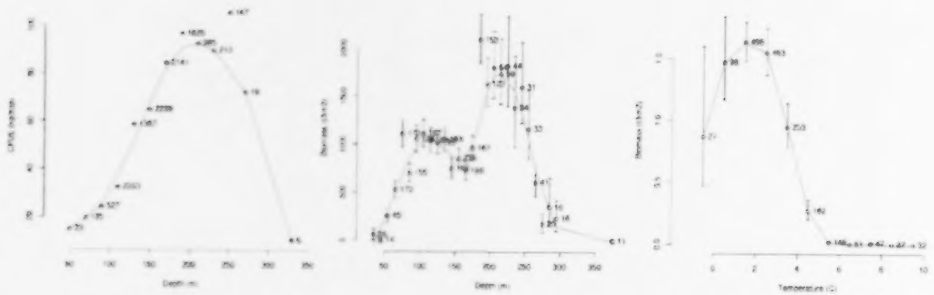


Figure 2. Habitat preferences of snow crab on the Scotian Shelf. From left to right: (1) Fishery catch rates (kg/th) as a function of trap depth (m); (2) fishable biomass densities (t/km^2) as a function of sampling depth (m); (3) fishable biomass densities (t/km^2) as a function of bottom temperature (°C). 1 standard error bars are presented with numbers indicating the number of stations or trap hauls. A loess filter was used for the heuristic trend line.

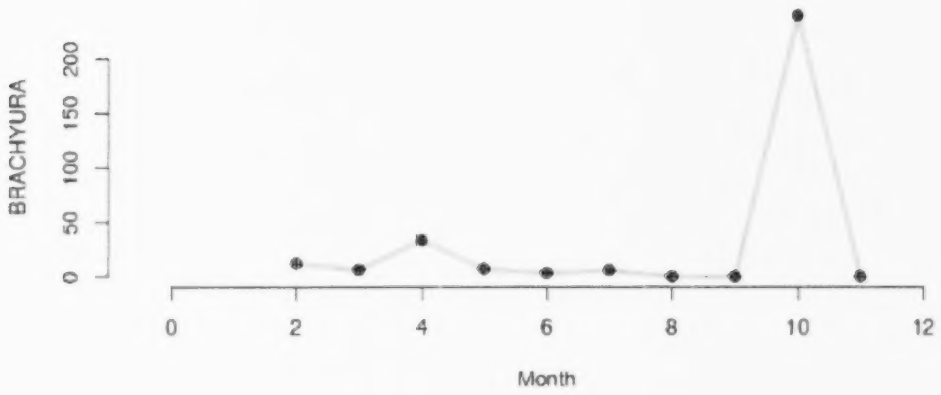


Figure 3. Monthly variations in the numerical density of Brachyura larvae in the eastern Scotian Shelf from various plankton monitoring systems ($number/m^3$). Note the sharp pulse of larvae in late autumn. Data courtesy of B. Petrie (Ocean Sciences Division, BIO, DFO).

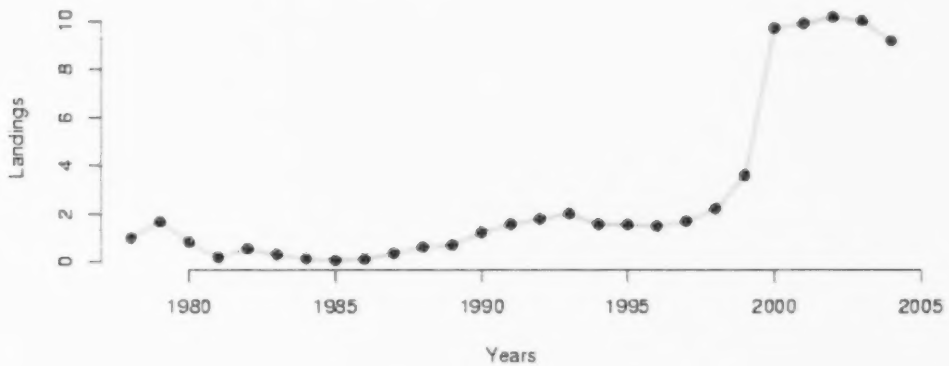


Figure 4. Temporal variations in the landings of snow crab on the Scotian Shelf (1000 t). Note the sharp increase in landings associated with dramatic increases to TACs and a doubling of fishing effort in the year 2000. The landings follow the TACs with little deviation (and so are not shown) indicating that the use of baited traps is very efficient at exploiting snow crabs. Nonetheless increased fishing effort was observed in the northern areas in recent years (see Figure 7).

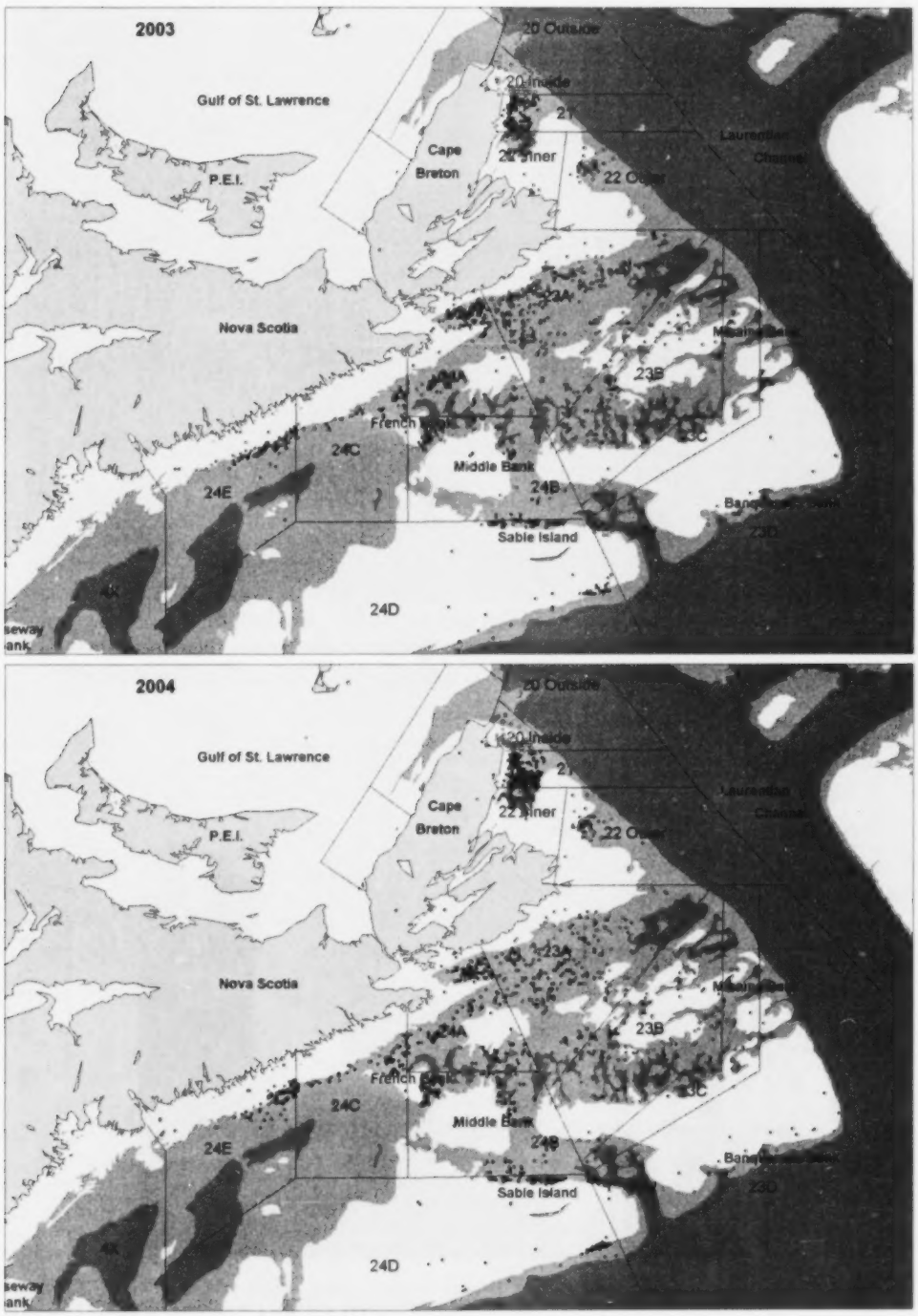


Figure 5. Fishing location on the Scotian Shelf for the years 2003 (upper panel) and 2004 (lower panel).

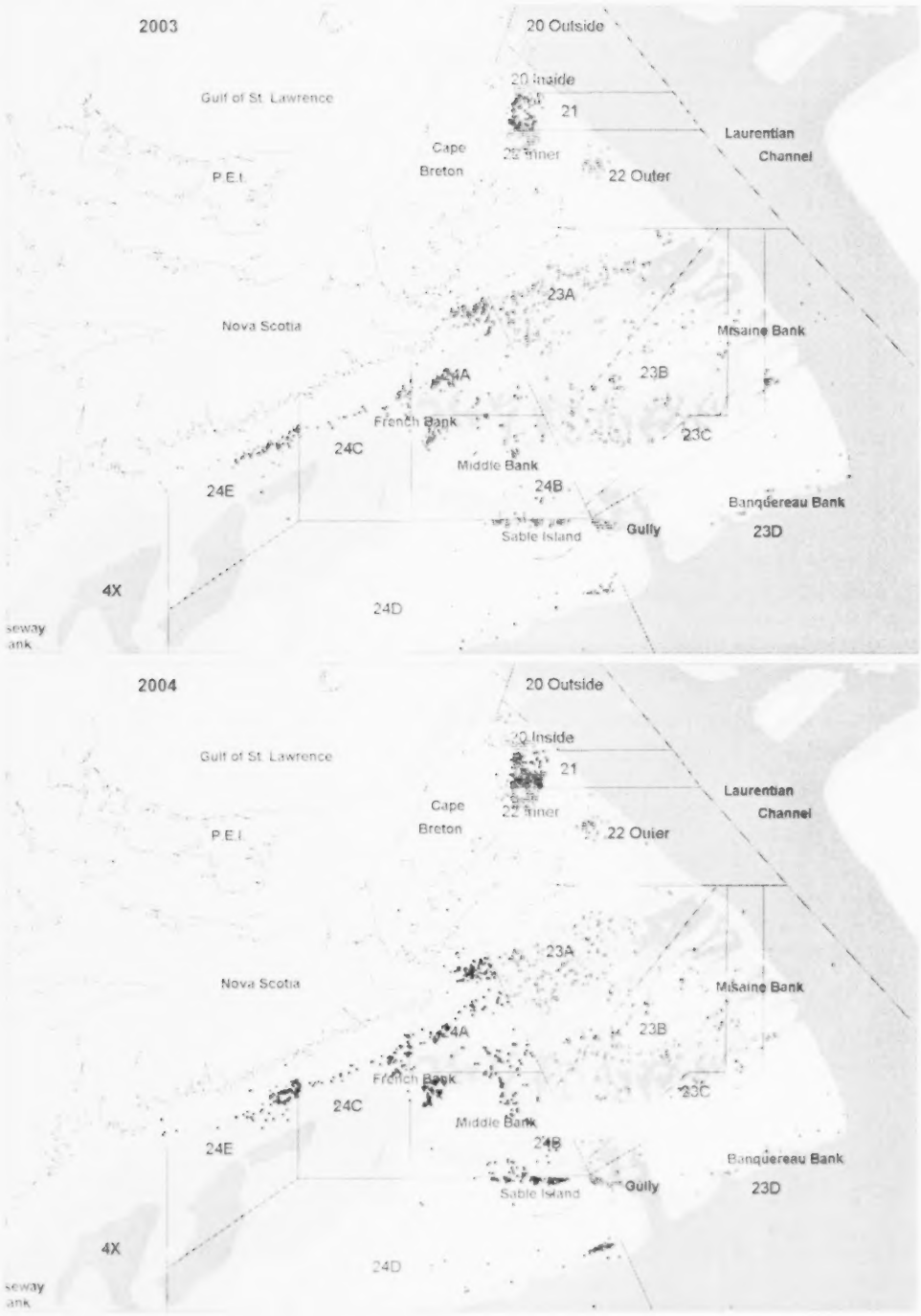


Figure 5. Fishing location on the Scotian Shelf for the years 2003 (upper panel) and 2004 (lower panel).

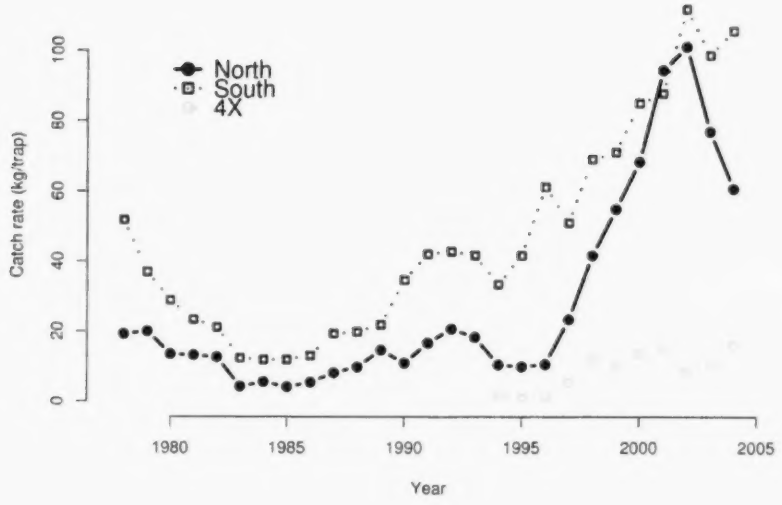


Figure 6. Temporal variations in catch rates of snow crab on the Scotian Shelf, expressed as kg per trap haul. Trap design and size have changed over time. No correction for these varying trap-types nor soak time and bait-type has been attempted.

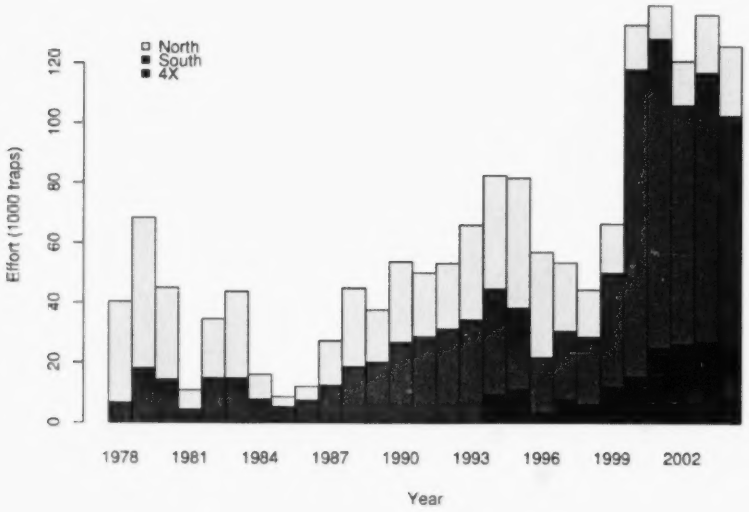


Figure 7. Temporal variations in the fishing effort, expressed as the number of trap hauls. Note the doubling of effort in the year 2000.

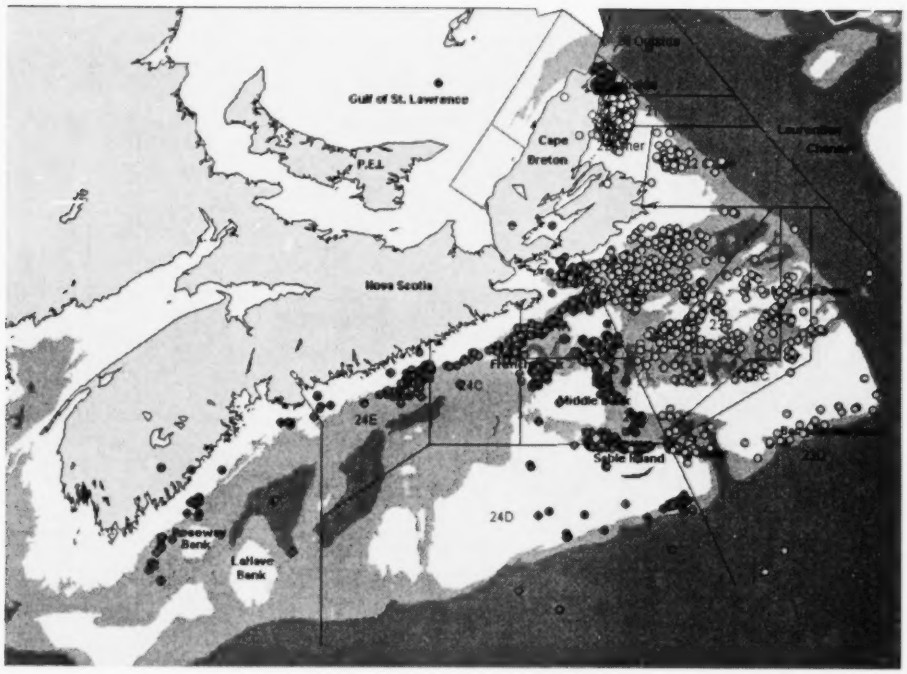


Figure 8. At-sea-observer monitored locations on the Scotian Shelf for the year 2004.

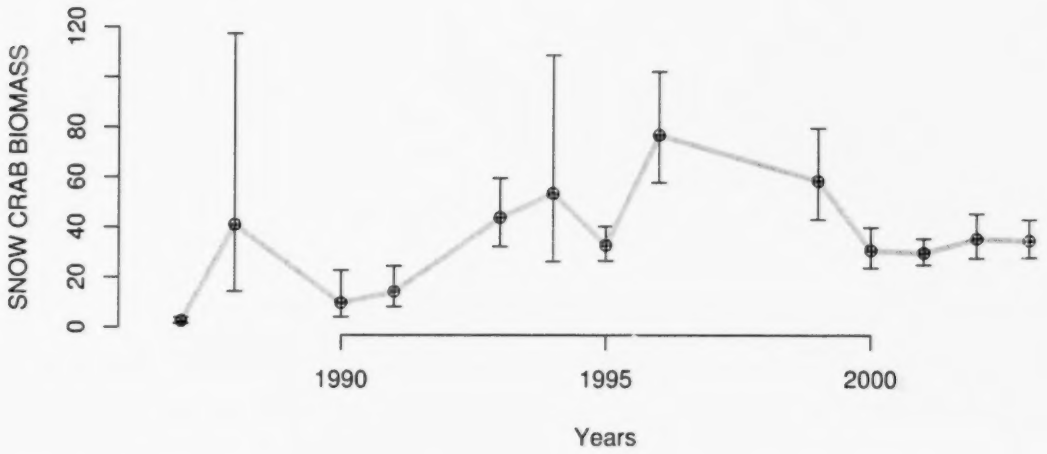


Figure 9. Annual variations in biomass estimates derived from the Groundfish Research Surveys in units of kg/km^2. Note the general qualitative trends of increasing biomass and the more recent declines. Data reliability prior to 1999 is low as the invertebrate monitoring protocol was not established. 1 standard error bars are presented. Biomass estimates are an order of magnitude lower than that obtained from a geostatistical approach adopted here.

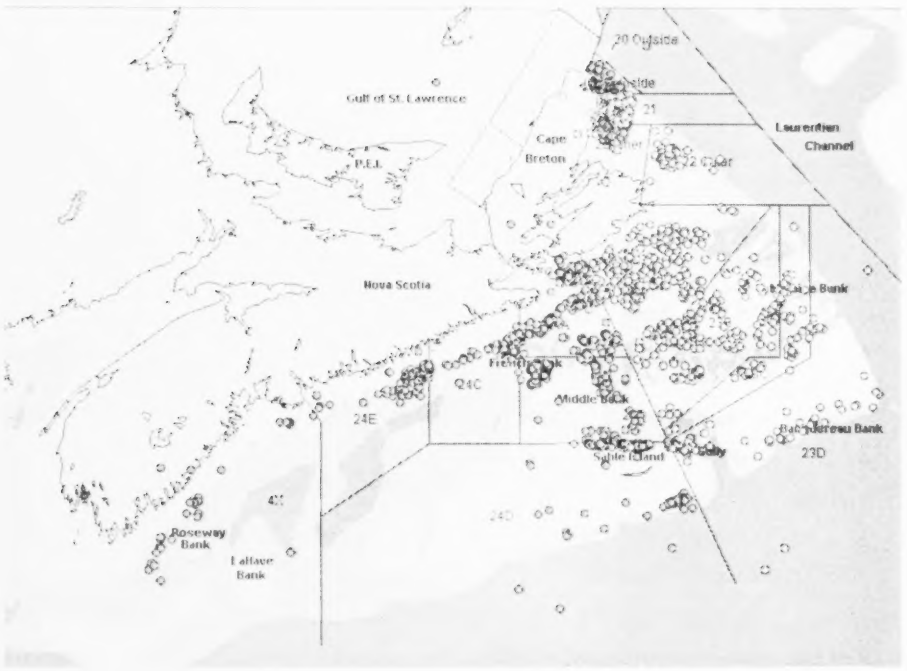
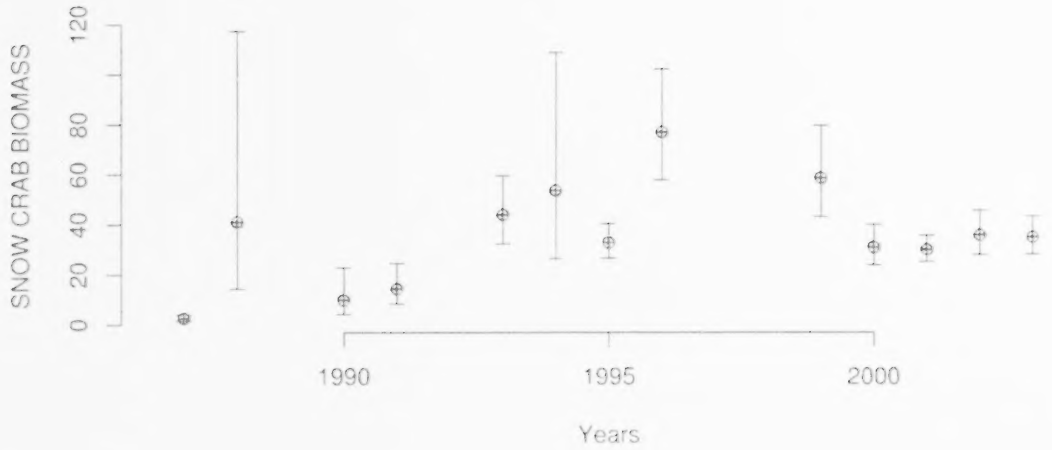


Figure 8. At-sea-observer monitored locations on the Scotian Shelf for the year 2004.



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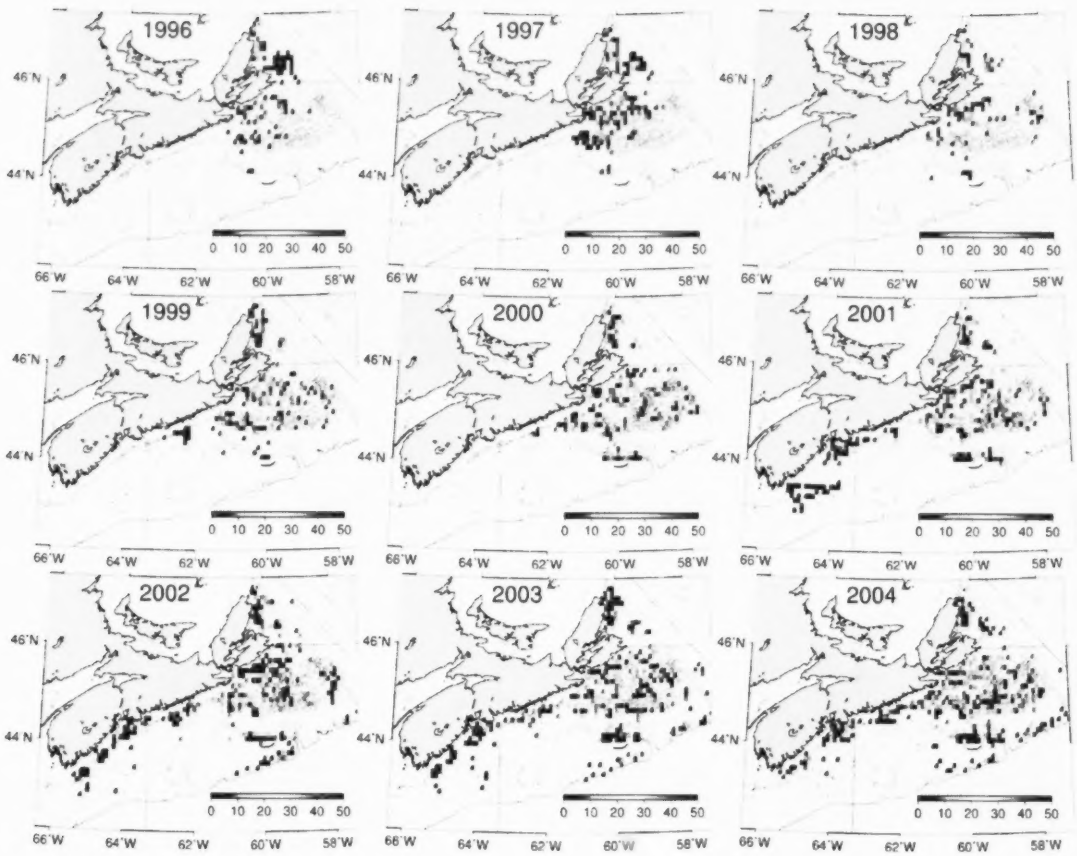


Figure 10. Crab landings (kg) from fisheries logbook data for the years 1996 to the present. Note the increase in landings offshore and reduction inshore for the southern CFAs. No visible changes are evident in the northern CFAs.

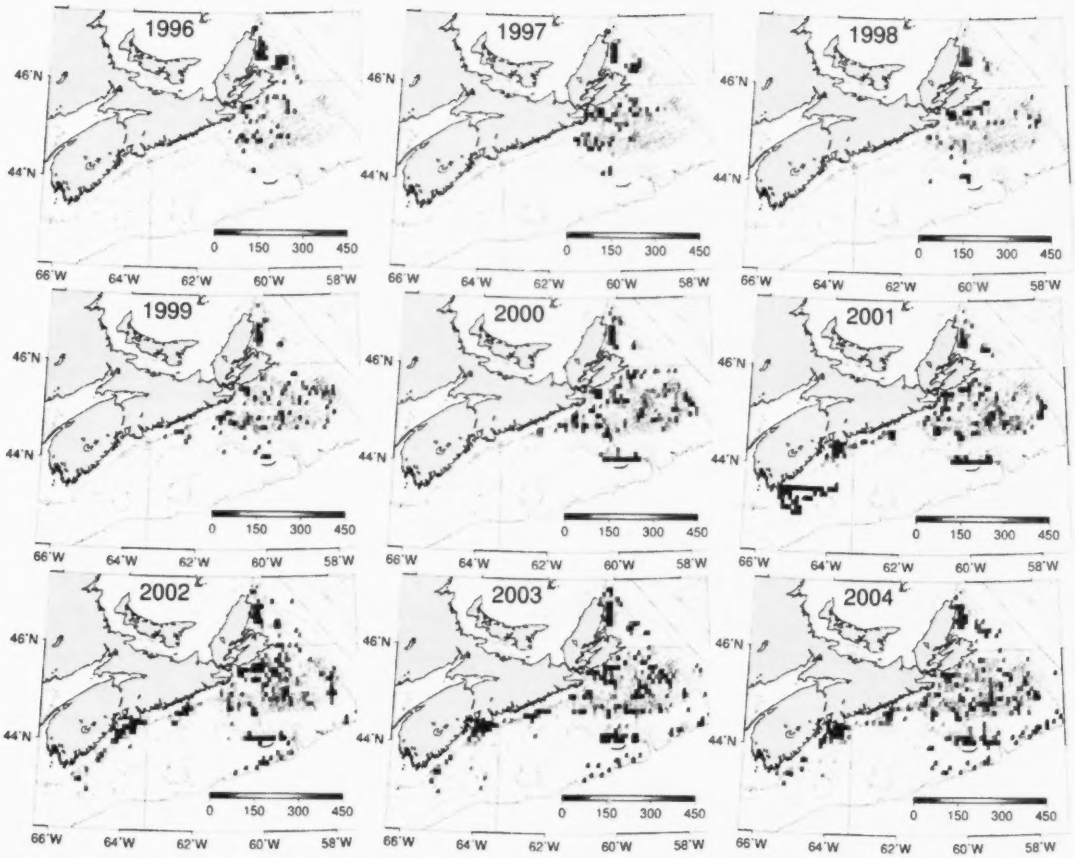


Figure 11. Fishing effort (number of trap hauls; th) from fisheries logbook data for the years 1996 to present. Note the increase in effort offshore and reduction inshore in the southern CFAs. No visible changes are evident in the northern CFAs.

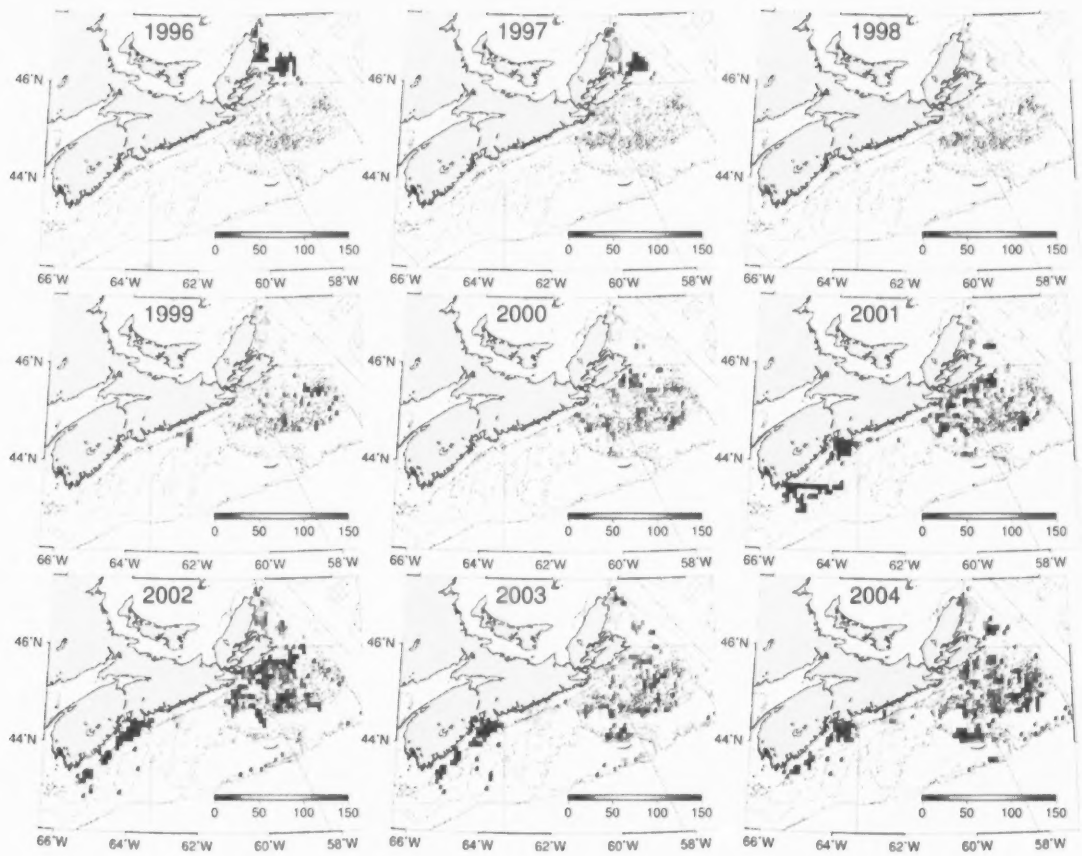


Figure 12. Catch rates (kg/th) from logbook data for the years 1996 to the present. Note the expansion of fisheries activity to more offshore locations with time. TACs were raised dramatically in 2000. Since that time, large decreases of catch rates in the inshore areas have become evident, indicating strong depletion. The movement to more offshore areas (in the southern CFAs 23 and 24) has offset this lowering of catch rates, where previously unexploited areas became more fully exploited. The temporal increases in crude catch rates of the southern CFAs are therefore due to the spatial expansion of the targetted areas and the fishers learning to find newer fishing grounds.

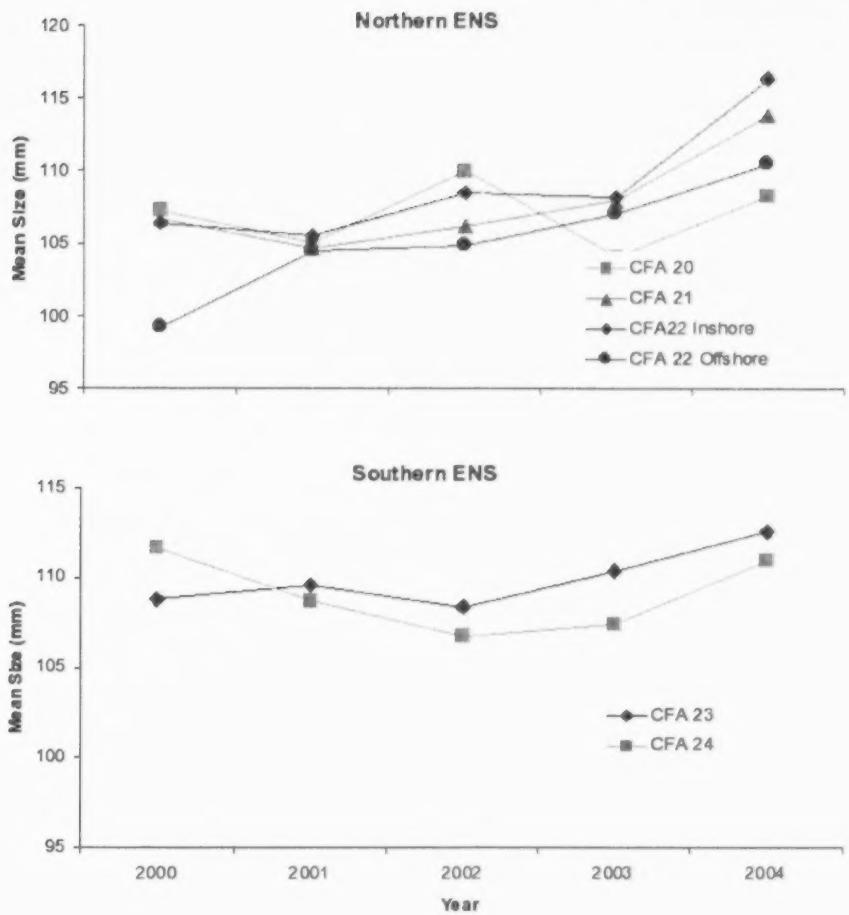


Figure 13. At-sea-observer monitored mean size (CW; mm) of catches on the Scotian Shelf in 2004.

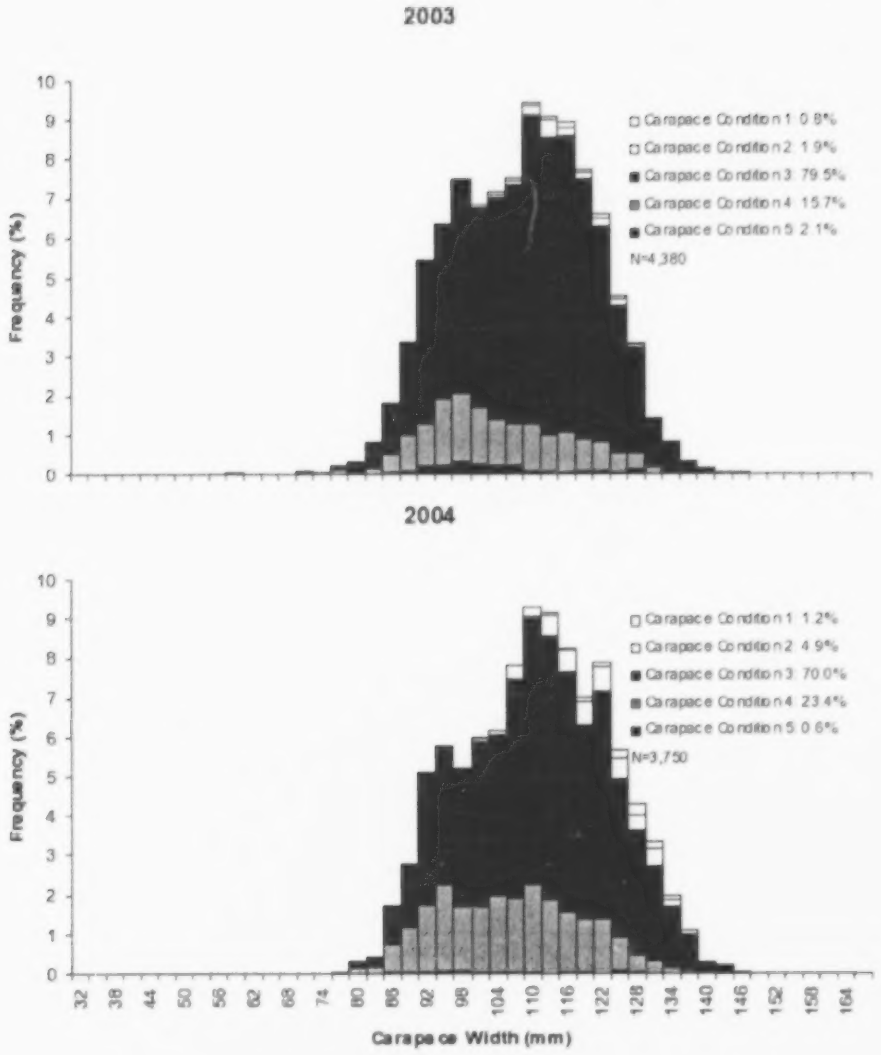


Figure 14. At-sea-observer monitored carapace condition as a function of CW for catches in northern CFAs (20 to 22) in 2004.

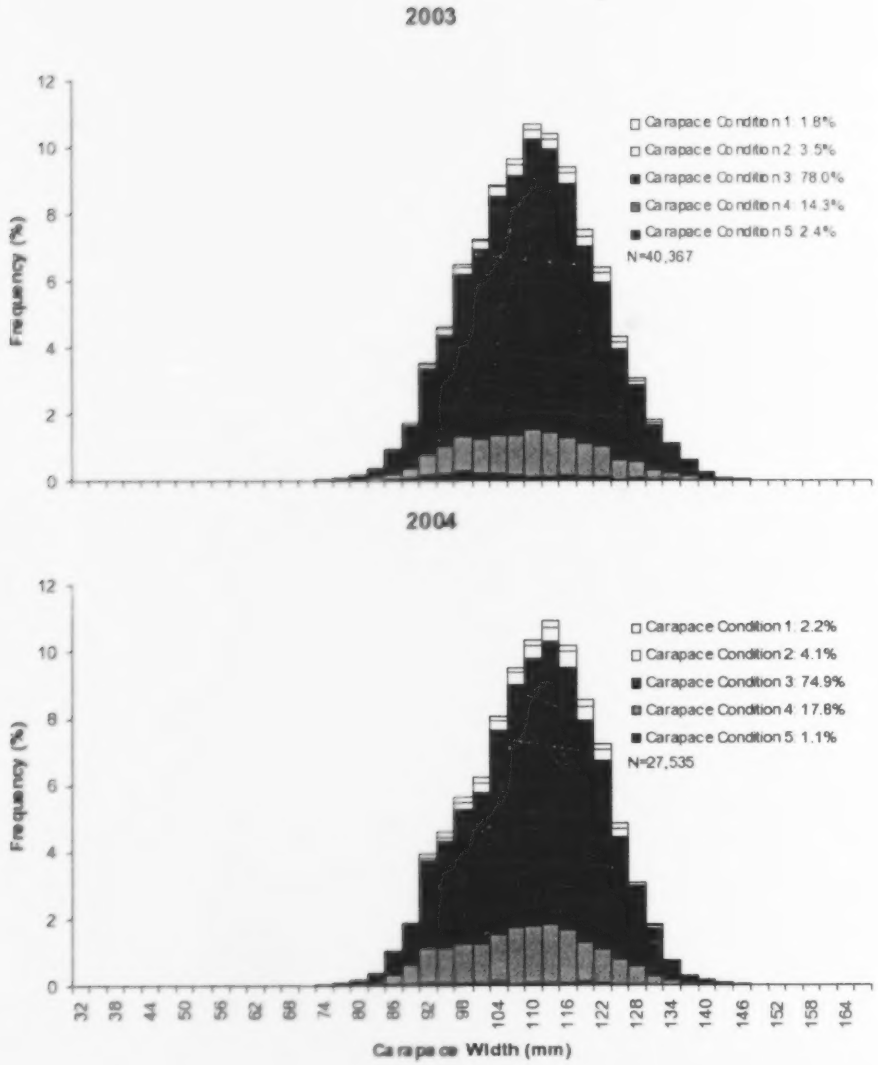


Figure 15. At-sea-observer monitored carapace condition as a function of CW for catches in southern CFAs (23 & 24) in 2004.

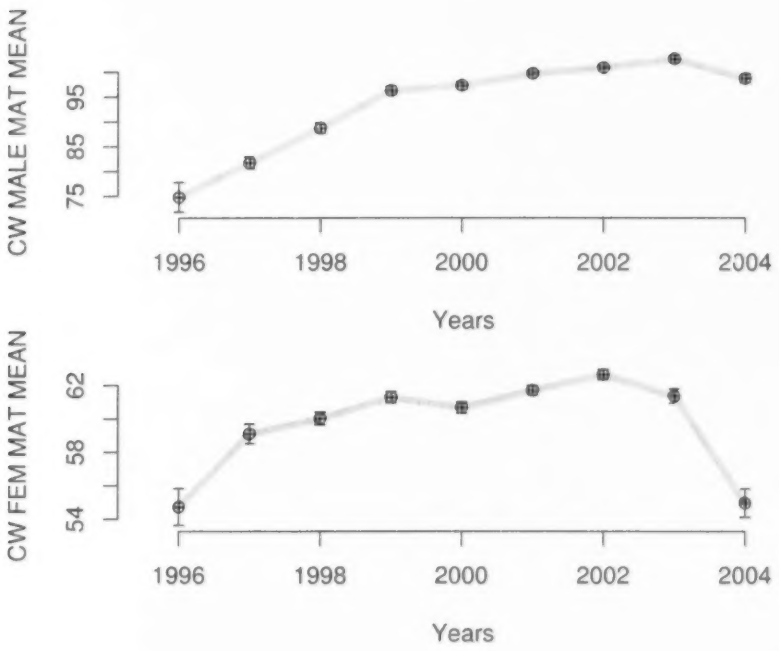


Figure 16. Annual variations in the geometric mean size of morphometrically mature males (top) and females (bottom). One standard error bars are presented. Note the increasing trend due to maturation and differential mortality of smaller individuals, with little recruitment in both sexes. However, in 2004 a sharp drop in mean size was observed, coincident with a new wave of mature females entering the system.

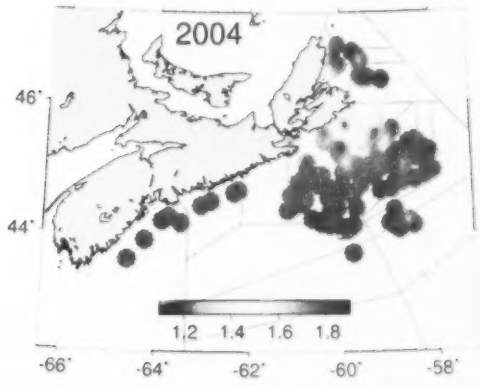


Figure 17. The location of the influx of small morphometrically mature females into the Scotian Shelf. The scale is logarithmic ($log_{10}(CW[mm])$). The main influx of the new females are towards the near-shore areas of CFAs 23A and 24A.

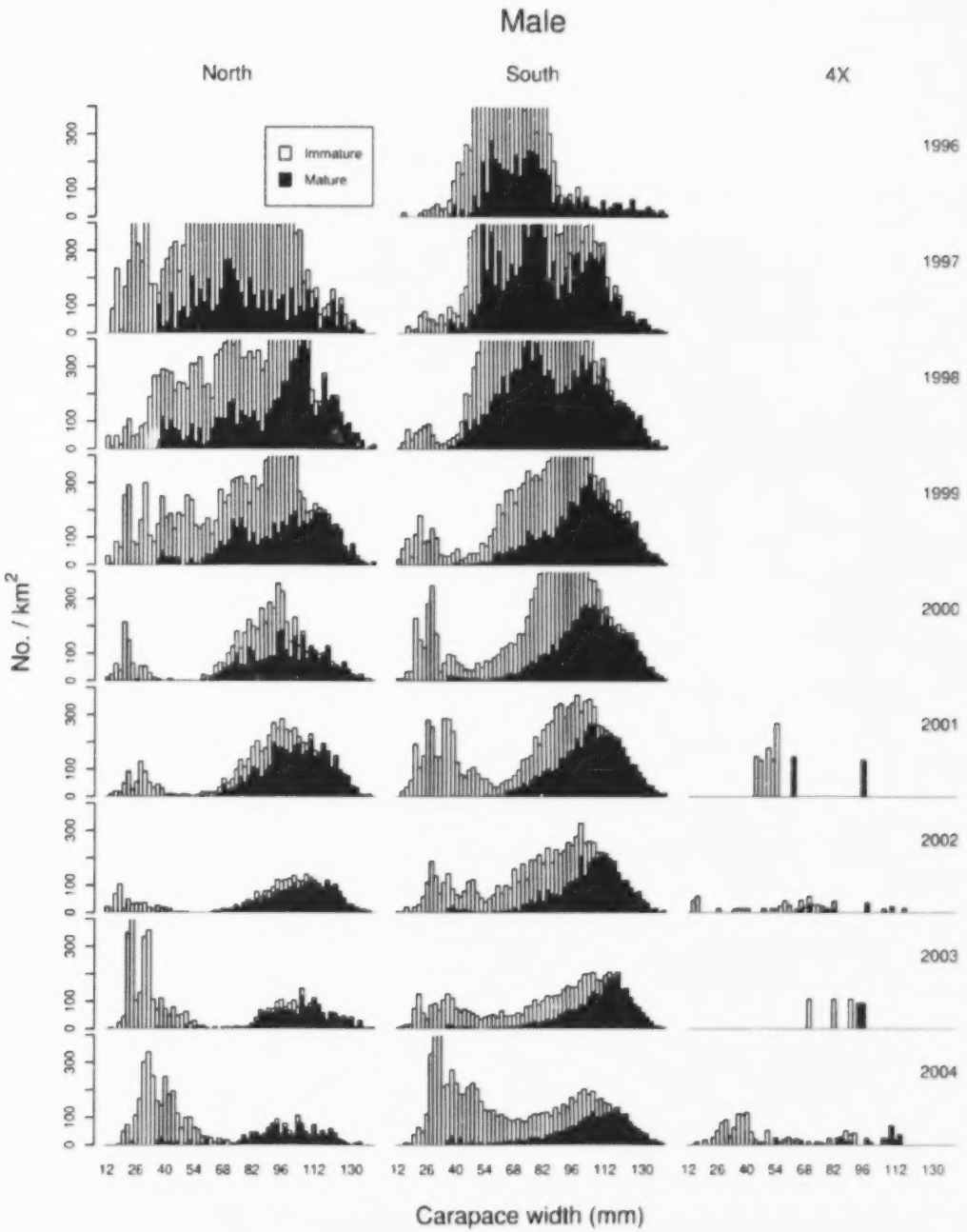


Figure 18. Size-frequency histograms of carapace width of male snow crabs. Note the increasing numbers of juvenile crab, 3 to 5 years from entering the fishable biomass.

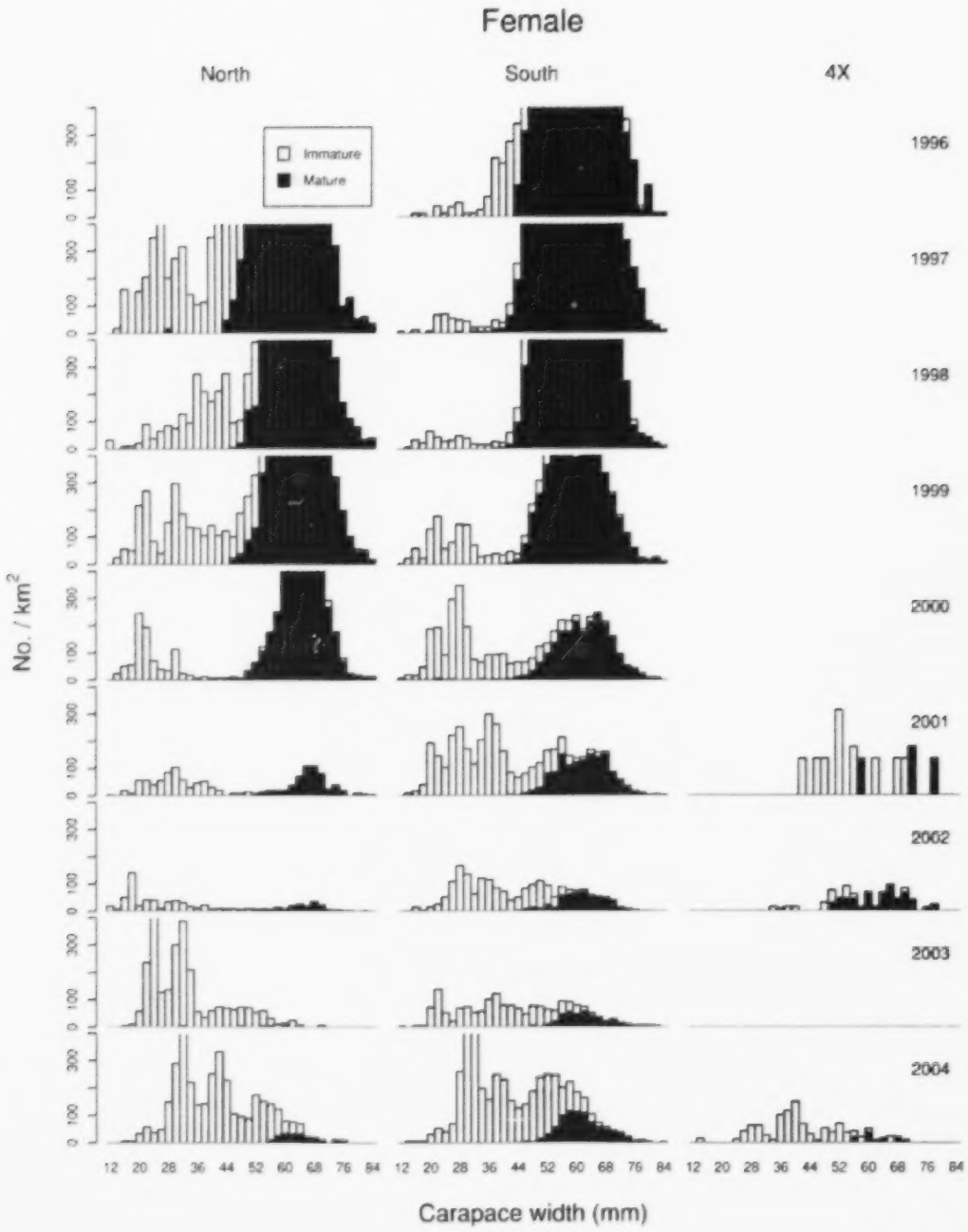


Figure 19. Size-frequency histograms of carapace width of female snow crabs. Note the increasing numbers of juvenile crab, 2 to 4 years from entering morphometrically mature size classes.

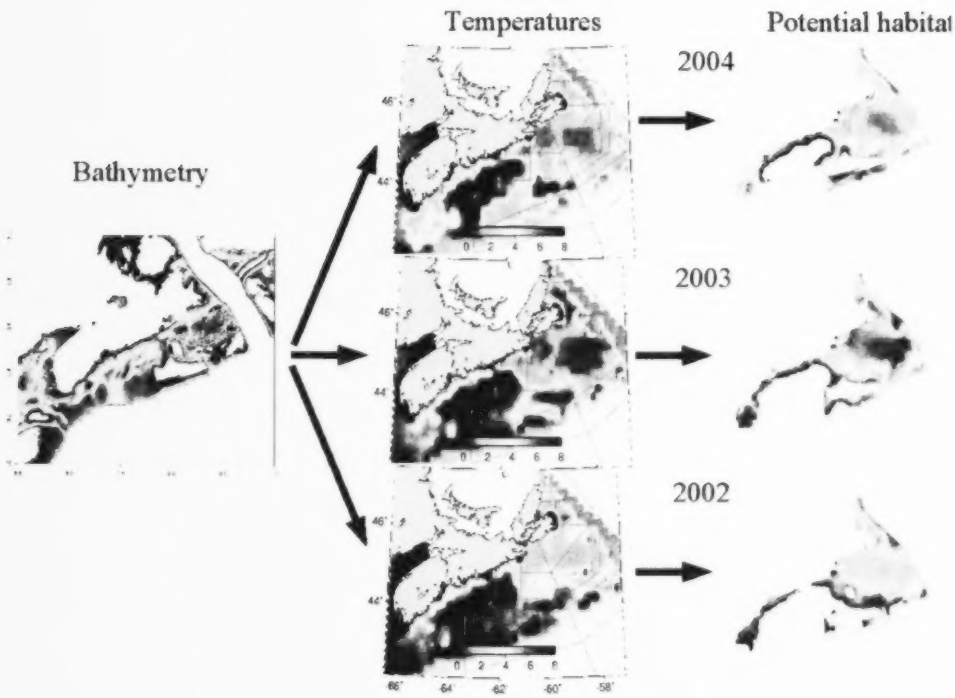


Figure 20. Schematic of geostatistical methods used to estimate fishable biomass.

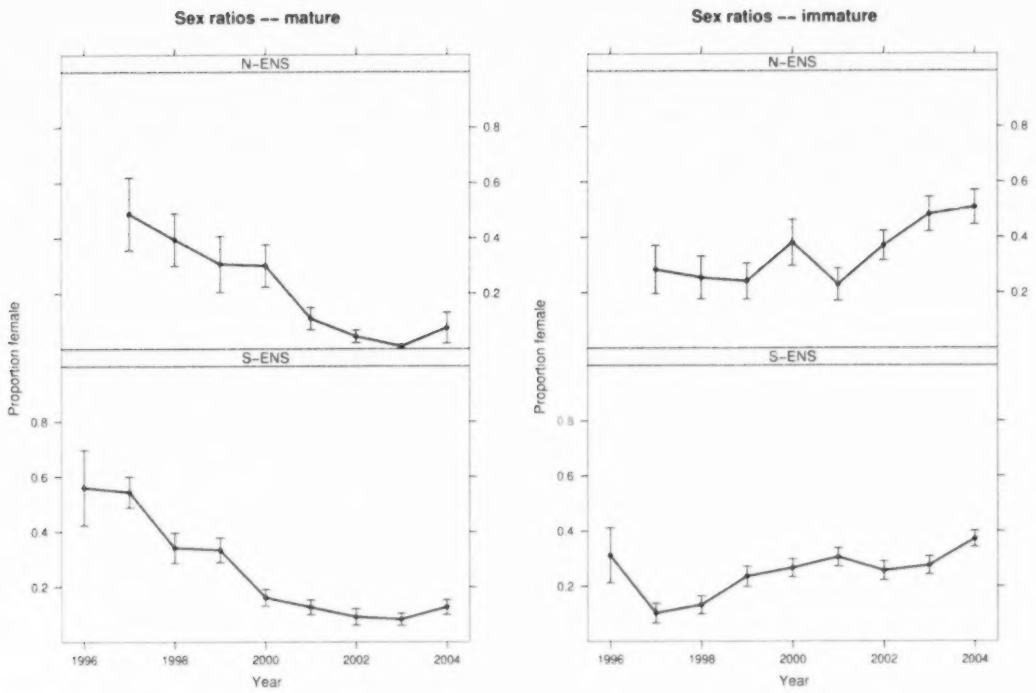


Figure 21. Annual variations in proportion female (sex ratios) for morphometrically mature crabs (**Left**) and immature crabs (**Right**). One standard error bars are presented. The mature sex ratios have been declining steadily since 1996 while immature sex ratios have been returning to more balanced proportions.

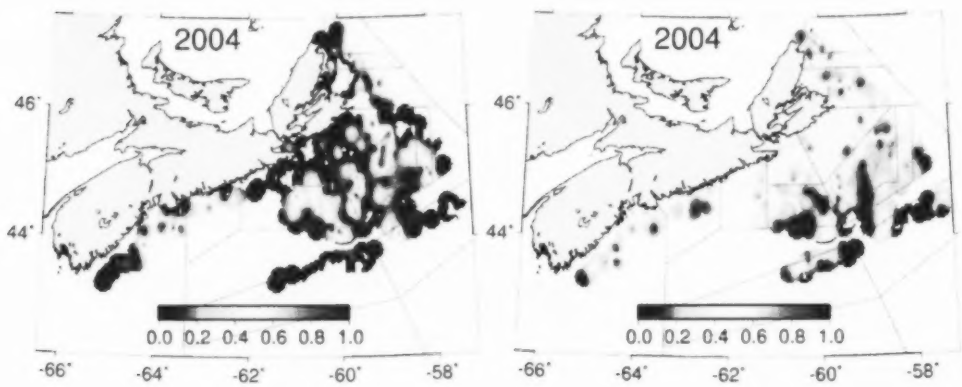


Figure 22. Left: Morphometrically mature sex ratios. Since 2000, most of the Scotian Shelf has been uniformly male dominated. A slight amelioration of the mature sex ratio was observed in 2004 (Figure 21 which was centered in the Misaine and Middle Banks and the nearshore areas of CFA 4X. **Right**: Morphometrically immature sex ratios. Inshore areas are generally more balanced in sex ratios or more female dominated. Offshore areas were more male dominated. In the past, this was not always the case and sex ratios of immature crabs were more heterogeneous.

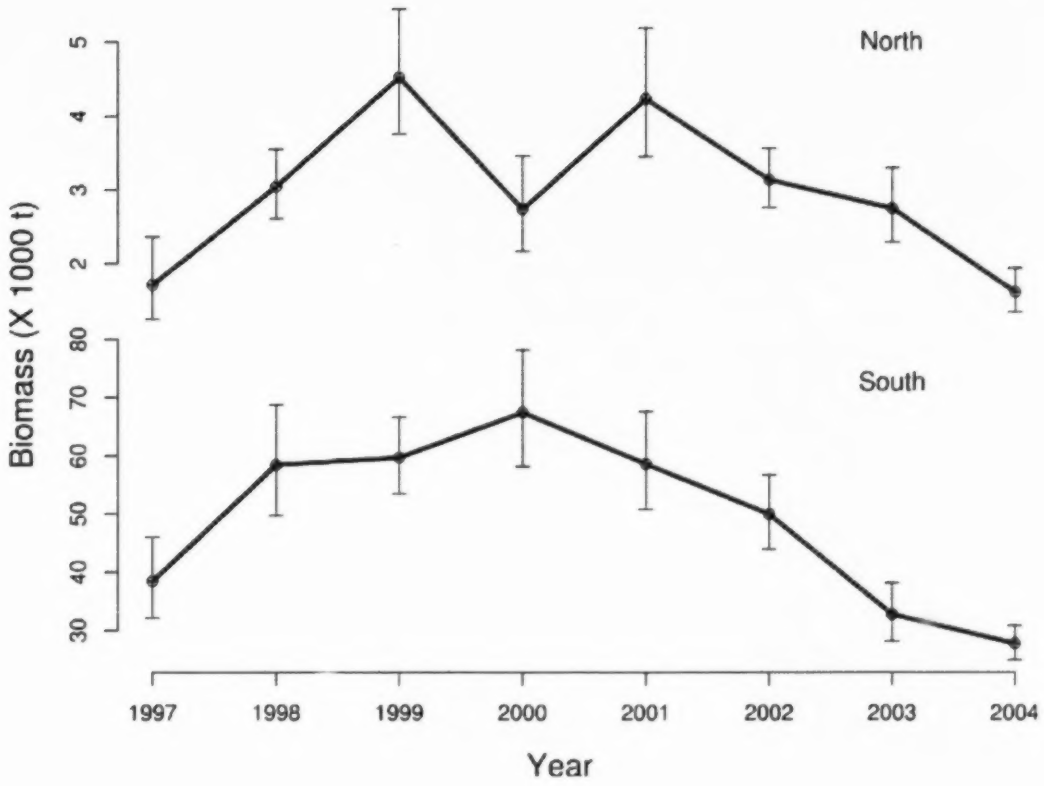


Figure 23. Temporal variations in the Kriged fishable biomass estimates. The biomasses from past years have been extrapolated to the areal extent of snow crab in 2004 to be comparable with this year's estimate. Error bars are 95% confidence intervals.

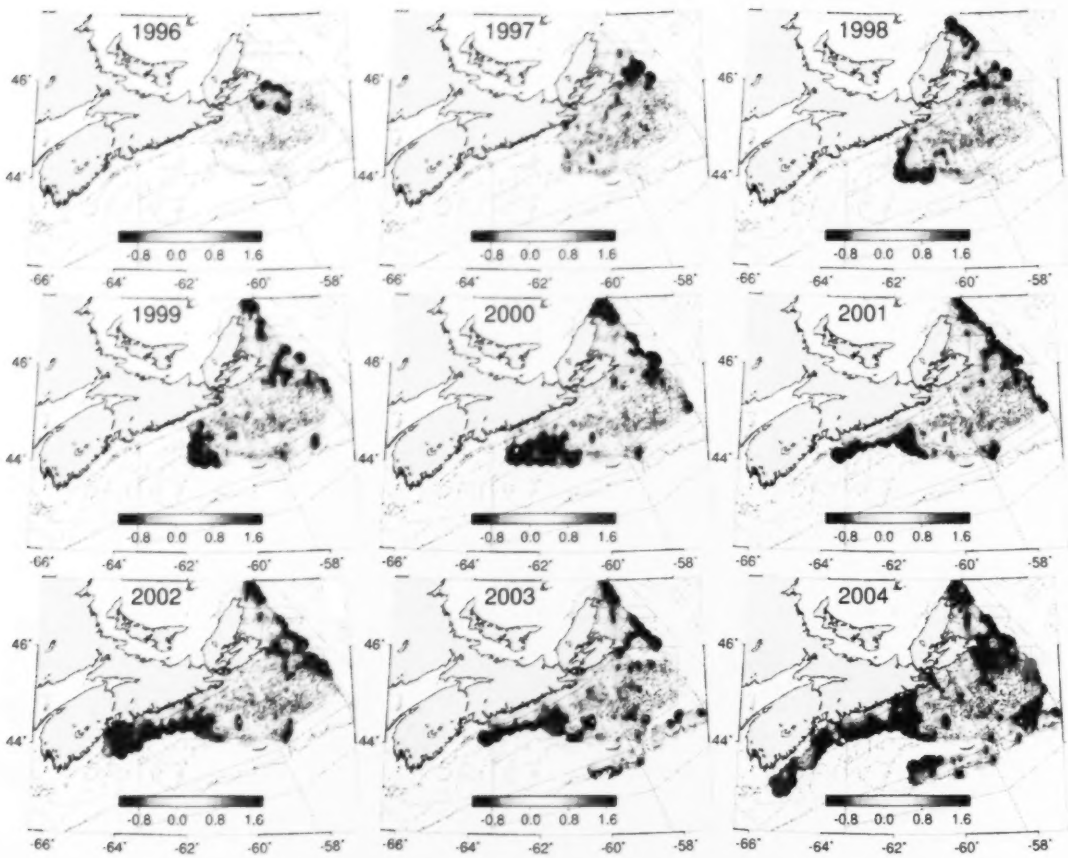


Figure 24. Map of fishable biomass densities on the Scotian Shelf; $log_{10}(t/km^2)$.

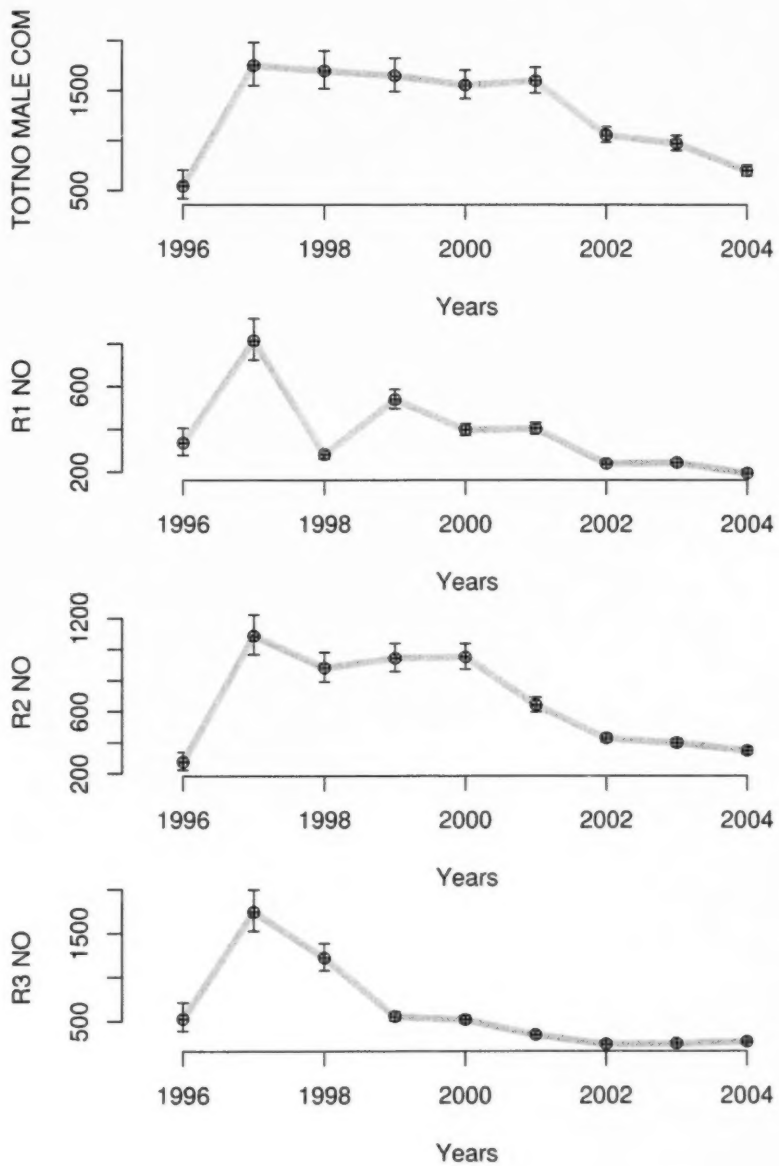


Figure 25. Whole of the Scotian Shelf population. Timeseries of geometric mean numerical densities ($number/km^2$) of male crabs for commerically size crabs (top), soft-shelled crabs that will recruit into the fishable biomass next year (R1), the second year (R2) and the third year (R3). 1 standard error bars are presented. See glossary for definitions for recruitment.

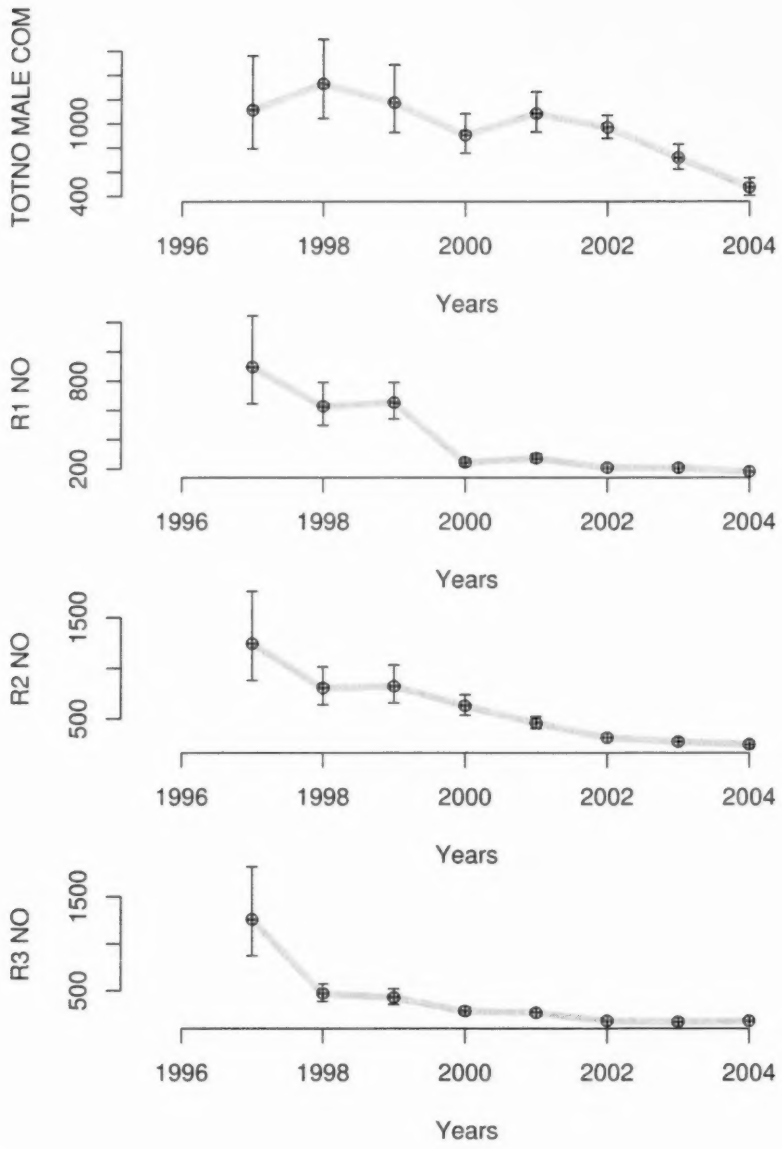


Figure 26. Northern CFAs: Timeseries of geometric mean numerical densities ($number/km^2$) of male crabs for commerically size crabs (top), soft-shelled crabs that will recruit into the fishable biomass next year (R1), the second year (R2) and the third year (R3). 1 standard error bars are presented. See glossary for definitions for recruitment.

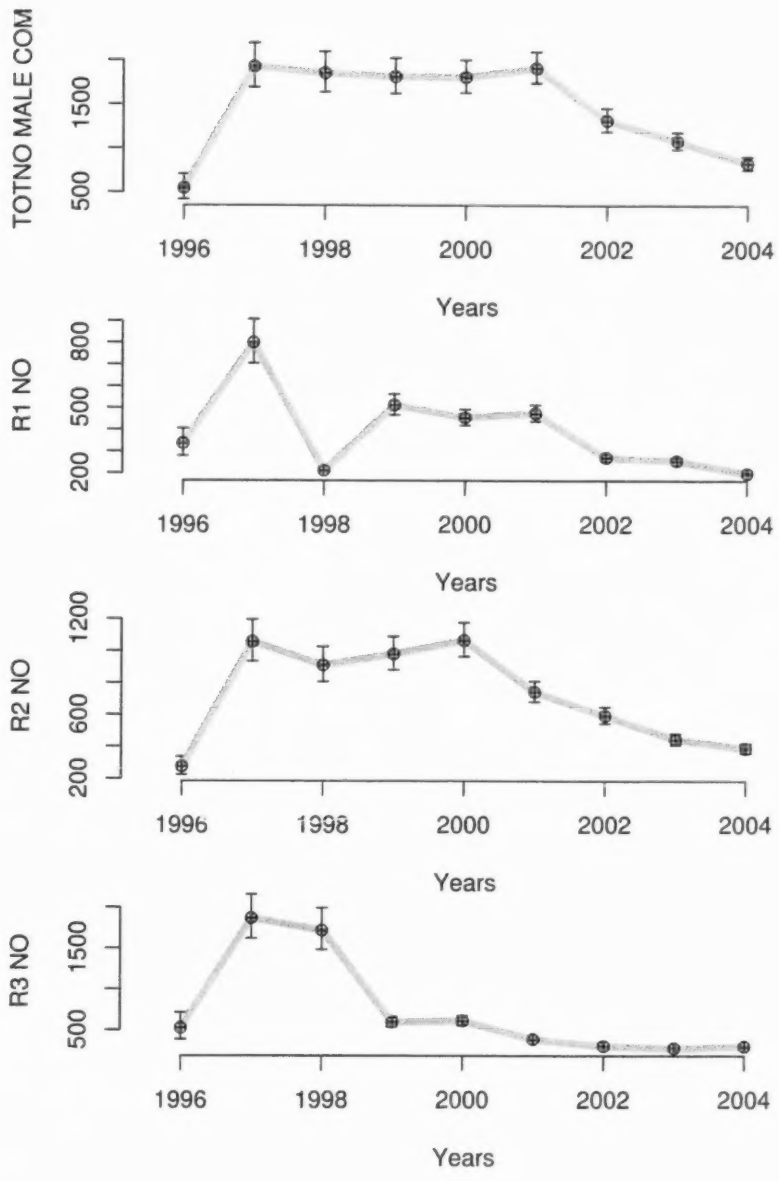


Figure 27. Southern CFAs: Timeseries of geometric mean numerical densities ($number/km^2$) of male crabs for commerically size crabs (top), soft-shelled crabs that will recruit into the fishable biomass next year (R1), the second year (R2) and the third year (R3). 1 standard error bars are presented. See glossary for definitions for recruitment.

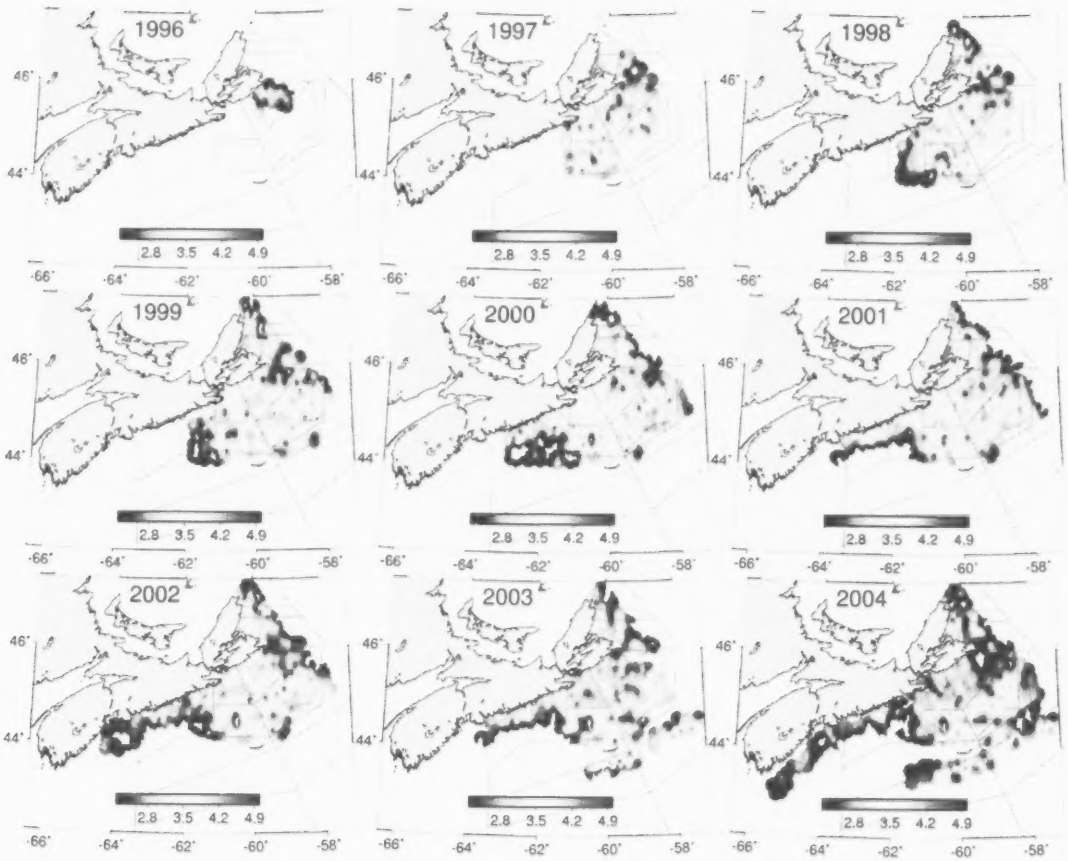


Figure 28. Map of numerical densities of the legal size crabs on the Scotian Shelf; $log_{10}(number/km^2)$.

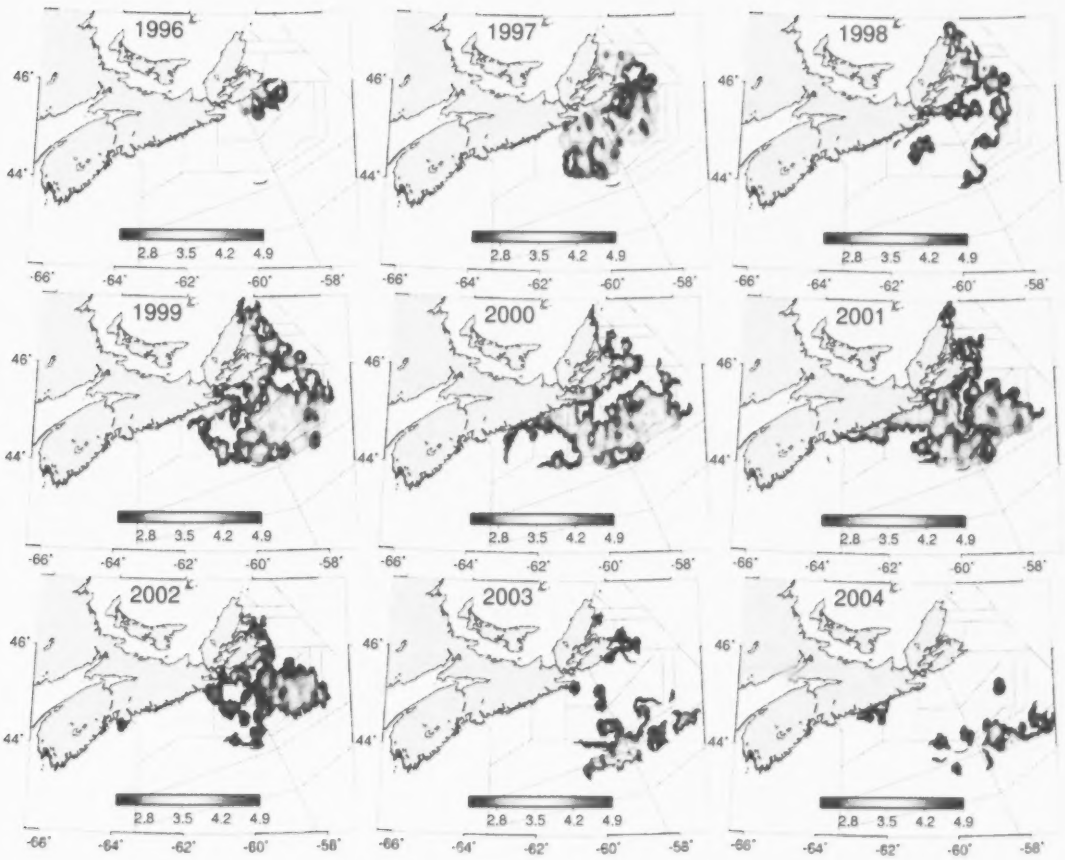


Figure 29. Map of numerical densities of R1 crab that will recruit into the fishable biomass next year; $log_{10}(number/km^2)$. See glossary for definitions for recruitment.

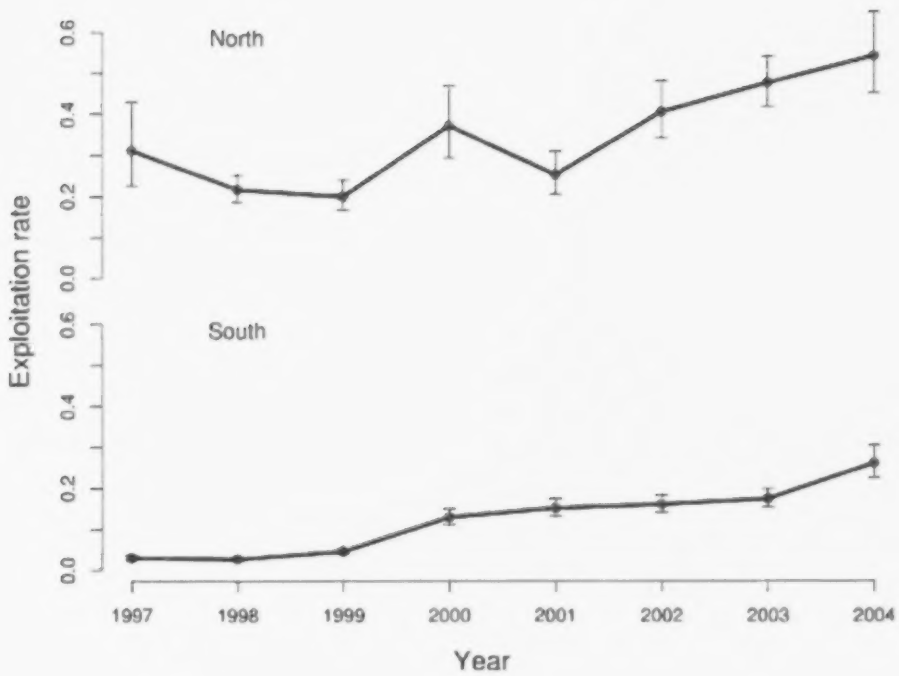
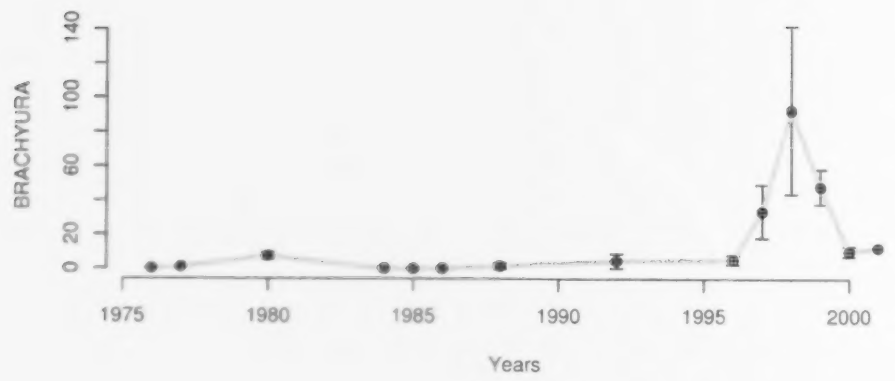


Figure 30. Temporal variations in the amount of biomass landed relative to biomass estimates. Note the rapid increase in 2004 exploitation rates even though the standing biomass has been declining.



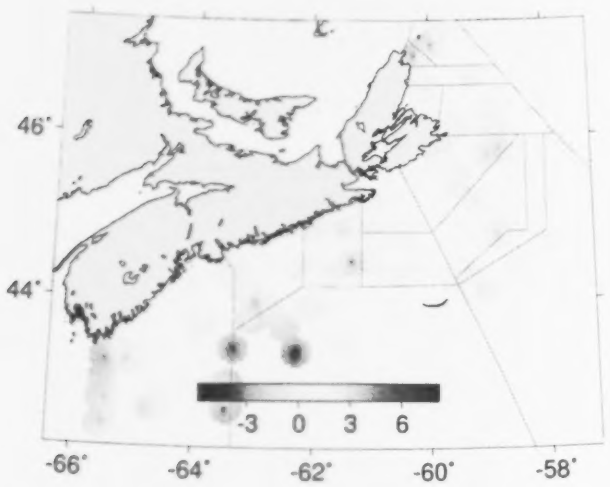


Figure 31. Top: Temporal variations in the numerical density of Brachyura larvae in the eastern Scotian Shelf from various plankton monitoring systems ($number/m^3$). Note the sharp pulse of larvae in the late 1990s, centered on 1998. This distinct pulse of larval release should become fishable in approximately 9 years. It is also indicative that the high abundance of reproductive crabs is indeed a recent phenomenon. Further, ≈ 9 years previous to this 1998 pulse (i.e, 1989) was when this dominant group of crab had their origins – the same period as the crash of the groundfish on the eastern Scotian Shelf. 1 standard error bars are presented. **Bottom**: Map of the numerical density of Brachyura larvae in the eastern Scotian Shelf from various plankton monitoring systems $log_{10}(number/m^3)$ from 1976 to 2001. Data courtesy of B. Petrie (Ocean Sciences Division, BIO, DFO).

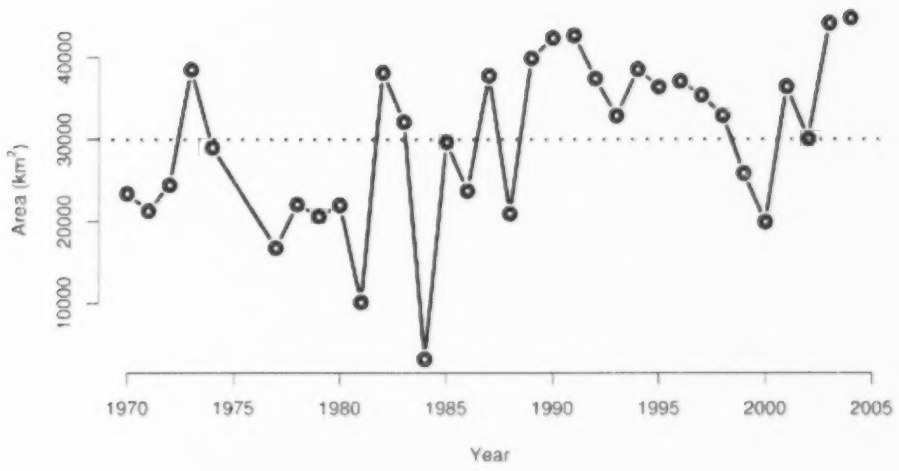


Figure 32. Average bottom temperatures on the eastern Scotian Shelf (°C). Note the generally cooler bottom temperatures since 1990. Data courtesy of D. Brickman (Ocean Sciences Division, BIO, DFO).

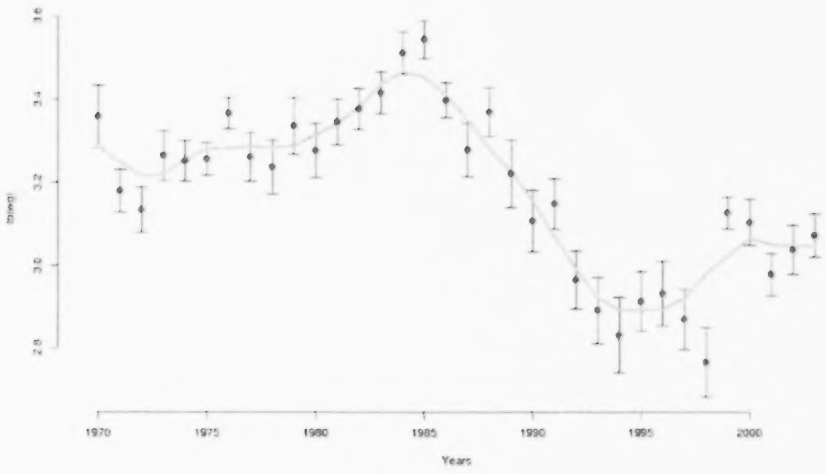


Figure 33. Variations of the biomass ($log_{10}mass\ \ [kg\ \ m^{-2}]$) of groundfish and elasmobranchs as a function of time based upon summer groundfish research surveys for the eastern part of the Scotian Shelf (NAFO area 4VW). 1 standard error bars are presented. Note the decline of biomass in the 1990s and a subsequent increasing trend since 1999. Note also the peak biomass of groundfish and elasmobranchs during the period of the snow crab fishery "crash" in the mid-1980s.

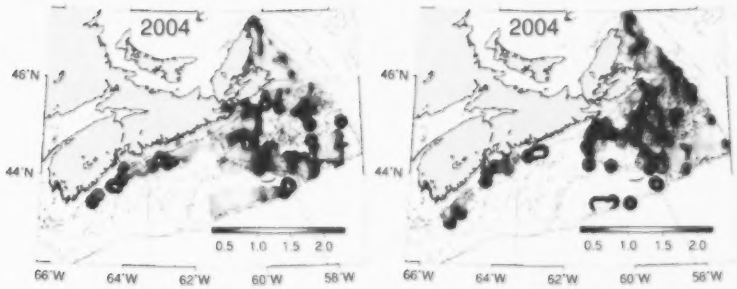


Figure 34. Locations of potential predators of snow crab: cod (top), thorny skate (bottom) sampled by the snow crab trawl surveys. Scale is $log_{10}(numerical\ \ density\ \ [number/km^2])$.

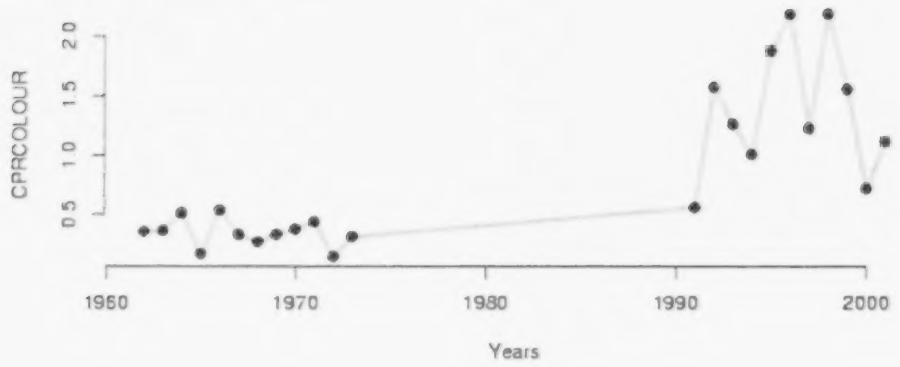


Figure 35. Timeseries of an index of phytoplankton abundance (colour intensity) from the Continuous plankton recorder monitoring program over the Scotian Shelf. Note the very different productivity of the system inferred from this data series.

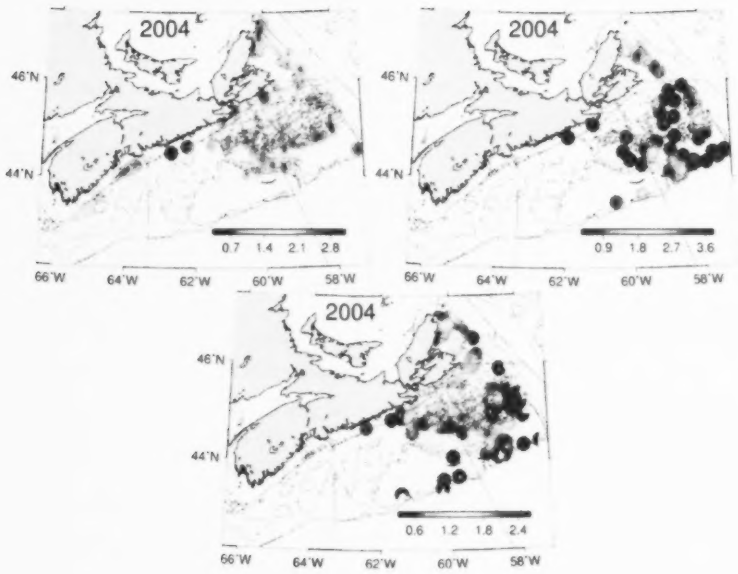


Figure 36. Locations of potential food items of snow crab sampled by the snow crab trawl surveys: northern shrimp (top, left), brittle star (top, right), basket star (bottom). Abundance of these potential food sources roughly match the spatial distributions of snow crab. Scale is $log_{10}(numerical\ density\ [number/km^2])$.

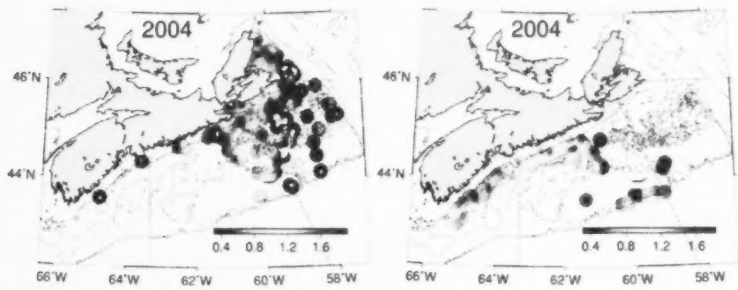


Figure 37. Locations of potential competitors of snow crab sampled by the snow crab trawl surveys: lesser toad crab (left), jonah crab (right). High competitive interactions are probable in inshore areas. Scale is $log_{10}(numerical\ density\ [number/km^2])$.

Glossary

Anthropogenic – Resulting from the influence of human beings on nature.

Benthic – Occurring on the ocean floor.

BIO – DFO, Bedford Institute of Oceanography located in Dartmouth, Nova Scotia.

Biomass – The abundance of living organisms measured in terms of it's weight, mass, volume or caloric energy.

Brachyura (Infraorder) – Known as "true crabs" of which the snow crab is a member. Brachyurans are characterised by a body that is short, wide, and flat. The abdomen, is reduced from a strong swimming muscle (e.g., shrimp) to a simple flap covering reproductive appendages and hold eggs. The uropods, which along with the telson form the tailfan in other decapods, are totally absent. All five pairs of walking legs are generally large with the first pair being chelipeds. The antennae and antennules are greatly reduced and originate before the eyestalks.

CC, Carapace Condition – The condition of the shell of a snow crab. Generally related to the age of the organism and the time since last moult. See Table 1 for more details.

- *CC1* - Newly moulted crab. The top of carapace is light brown and shiny without surface growth of moss or barnacles. Shell is soft and claw is easily broken.
- *CC2* - The top of carapace is light brown and less shiny with little to no surface growth of moss or barnacles. Shell is clean but hard.
- *CC3* - The top of carapace is light brown and not shiny. Some growth of moss or barnacles. Shell is hard.
- *CC4* - The top of carapace is brown and not shiny. Usually some surface growth of moss or barnacles. Shell is hard with small scars. Underneath is yellow brown.
- *CC5* - Old crab. Carapace is dark brown with substantially mossy ("dirty") surface. Decalcification (black spots) noticeable often at joints. Shell may be soft.

CW, Carapace width – the distance across the carapace of a snow crab (millimetres)

CFA, Crab fishing area – Refers to individual management area. On the Scotian Shelf they are from north to south: 20 to 24 and 4X.

Commercial biomass – The biomass of snow crab which are legally exploitable by the commercial fishery: size $\geq$ 95 mm and hard shell condition (Carapace conditions 2 to 5). Note that Carapace condition 2 snow crab do not have optimal meat yields at the time of the fishery. Note also that immature crab larger than 95 mm are also part of the fishable biomass.

CPUE, Catch per unit effort – The amount caught by a single fishing event: such as the weight or number of crab captured by a single trap haul.

Density – The amount (biomass or number) of crab per unit area.

Distribution, spatial – The geographic area in which an organism exists.

Durometer – A calibrated instrument used to measure the hardness of an object (such as a crab shell), scaled from 0 (soft) to 100 (hard). A durometer reading of 68 or greater has been historically used to determine a hard shelled crab.

Dynamic – Characterized by continuous change or time. Not fixed.

Ecosystem – The whole of a system with all the interactions between parts (living and non-living).

ENS – Eastern Nova Scotia. N-ENS refers to the northern part of the Scotian Shelf, specifically the CFAs 20 to 22. S-ENS refers to the southern part of the Scotian Shelf.

ER, Exploitation rate – The ratio of biomass fished relative to their abundance. That is: ER(t) = Landings(t) / Biomass(t-1), where t is time or year. The Biomass was of the fishable segment of the male population $\geq$ 95 mm in CW, estimated from kriging.

Extrapolate – To infer or estimate by extending or projecting known information.

Fishable biomass, FB – see Commerical biomass.

Fishing mortality, relative – see Exploitation rate.

GFC – DFO Gulf Fisheries Center in Moncton New Brunswick.

IBQ – Individual Boat Quota, the amount of snow crab allowed to be legally removed by an individual fisher in a given area over a given period of time.

Instar – A stage in an organism between moults.

Interpolation – The method of determining intermediate values through the use of surrounding known values.

Kriging – A method of interpolation for obtaining statistically unbiased estimates of intrinsic variables (i.e., snow crab biomass density) from a set of neighbouring points with known values, constrained by the relative change in variability of the data as a function of distance.

Larva – The early, immature form of any animal before the assumption of the mature shape.

Metabolic costs – The amount of energy dispensed by an organism in the process of living (heat, organic compounds, faeces, etc.).

Metabolic gains – The amount of energy gained through the intake of food or other energy sources.

Morphometric maturity – Maturity status determined from measurements of body shape and size. Male snow crab claw height grows very rapidly in the adult stage (terminal moult), whereas females' abdominal width increases with maturity. While morphometric maturity generally co-incides with physiological maturity, morphometrically immature males are known to be able to fertilise females.

Moult – The act of growing through the shedding of an organism's current shell.

Multiparous – Females bearing eggs resulting from their second or third breeding event (mating).

Numerical density – The number of snow crab in a given surface area.

Pelagic – Occurring in the water column (not on bottom).

Physiological maturity – Biologically (functionally) able to reproduce.

Primiparous – Females bearing eggs resulting from their first breeding event (mating).

Recruitment – Snow crab that will enter the fishable biomass. The GFC defines a recruitment index as follows:

- *R1* - recruitment expected for the next year: males with CW $\geq$ 95 mm and with a soft shell at the time of the survey
- *R2* - recruitment expected in 2 years: males with CW $\geq$ 83 mm and $<$ 95 mm
- *R3* - recruitment expected in 3 years: males with CW $\geq$ 69 mm and $<$ 83 mm
- *R4* - recruitment expected in 3 years: males with CW $\geq$ 56 mm and $<$ 69 mm

where each category is nominal and some unknown fraction of the individuals may be expected to recruit.

Soft shell – Carapace condition in which the shell produces a durometer reading of less than 68.

Spatial – Relating to space (such as a given geographic region such as the Scotian Shelf).

Substrate – Habitat; bottom type on which an animal exists (rocks, boulders, mud, sand, etc.).

TAC – Total Allowable Catch, the amount of snow crab allowed to be legally removed in a given area over a given period of time.

Temporal – Relating to time (such as a given period of time).

Terminal moult – Snow crab moulted for a final time once mature. The size of these crab will not increase further.

Variogram – The manner in which the variability of data changes with distance from a given location. Empirical variograms depict the data-derived variation as a function of distance. Theoretical/modelled variograms are fitted curves which are ultimately used by the kriging methodology.